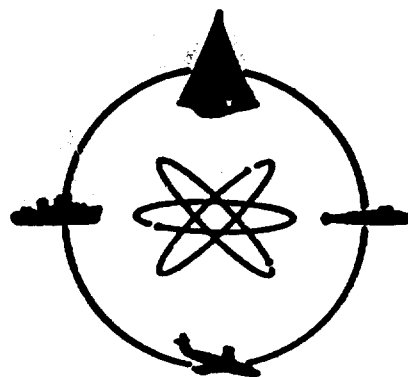# DAVIDSON

LABORATORY

Report 1285

April 1970

STUDIES OF OFF-ROAD VEHICLES IN THE
RIVERINE ENVIRONMENT
Vol. III. Associated Environmental
Factors

by

R. Ehrlich
G. Kolb
A. Sloss
and
M. Corridon

Prepared for the
U. S. Army Tank-Automotive Center
under
Contracts DA 30-069-AMC-789(T),
DAAE-07-69-C-0356,
and Stevens Internal Research Funds

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DAVIDSON LABORATORY

STEVENS INSTITUTE OF TECHNOLOGY
Castle Point Station
Hoboken, New Jersey 07030

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STUDIES OF OFF-ROAD VEHICLES IN THE RIVERINE ENVIRONMENT
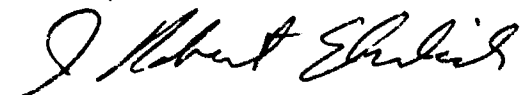## Volume III. Associated Environmental Factors

by

I. R. Ehrlich
R. G. Kolb
D. A. Sloss
and
L. M. Corridon

Approved

I. Robert Ehrlich, Manager
Transportation Research Group

xiii + 94 pages
24 figures

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the United States Government.

ABSTRACT

This report is a highly generalized overview of problems bearing upon the relationship of the riverine environment to vehicle stream crossings in unmapped or poorly mapped areas. Extractions from published works are used to emphasize (1) the need for reliable methods of predicting the nature of inland waters and neighboring terrain, from available climatic and geological data, and (2) the need for continuing and validating the theoretical study of vehicle performance in stream crossing and bank negotiation. It is made clear that a coordination of all factors into a comprehensive systems analysis would require a major effort, before the kind of evaluation method envisioned as the long-term goal of the current study can be achieved.

Keywords

RIVERINE ENVIRONMENTS

    Prediction of Environment
    Prediction of Stream Characteristics

OFF-ROAD VEHICLE MOBILITY

    Stream Crossing
    Bank Negotiation
    Environmental Factors

CONTENTS FOR VOLUME III

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FOREWORD TO VOLUMES I, II, AND III

One of the most important considerations in the development of
military vehicles has been the recent recognition that, to achieve true
cross-country mobility, a vehicle must possess the capability of crossing
inland waterways. This fact added a new dimension to the problems
confronting those faced with the responsibility for the design and
development of new military vehicle concepts. In order to incorporate this
new parameter into future designs, it is quite logical to turn for guidance
to the designers and developers of amphibious vehicles, who have for some
time been confronted by similar problems. It is in this context that the
studies discussed in these three volumes were undertaken. Although the
purpose of the work was originally intended to aid in the design of 1/4-ton
floating vehicles, the information presented is applicable to land vehicles
in general; hence, this document may be considered as a guide to methods
for evaluating all types of land vehicles relative to their performance in
crossing inland waterways.

There are two distinct aspects of vehicle evaluation:

(1) First, it is necessary to determine functional relationships
between the vehicle and its environment so that its performance capabilities
may be expressed in quantitative form.

(2) Second, to determine the vehicle's actual effectiveness, it is
then necessary to compare these performance capabilities with appropriate
quantitative environmental attributes of the inland waterway population
(or some sub-set thereof of military interest). In view of the present
state of knowledge in vehicle mechanics and environmental sciences, the
attainment of these objectives represents a tremendous task. The work
presented in this report constitutes a compendium of applicable knowledge
in this area, with progress naturally more advanced in some areas than
others, and it provides, moreover, a meaningful conceptual framework for
continued work by indicating the knowledge gaps that exist.

Three different modes of locomotion will be discussed in connection with the general stream-crossing maneuver: fully floating, fully land-borne, and water-land transition. In addition, operational techniques which really do not fall in any of the above three categories will be presented. Finally, th. ociated environmental factors relevant to all three modes will be discussed separately.

At its inception, the present program was designed to concentrate most heavily on various aspects of the fully floating mode, and much of the effort to date has been directed toward the development of vehicle-environment relationships for the fully floating case. Major consideration has been given to such factors as hydrodynamic resistance, propulsion effectiveness, freeboard requirements, and the effects of waves. These are areas in which a sophisticated technology has already been developed by the naval architect, but where applications to the design and evaluation of amphibious vehicles or ships having vehicle-like forms have been extremely limited.

Relationships between the fully land-borne vehicle and its environment (terrain) have been under intensive investigation for many years, notably under the auspices of the U. S. Army. The task for the present study is to particularize the previously developed models to the bank environment where the proximity of the stream or river is known to affect the soil and vegetation.

The aspect of stream-crossing performance about which least is known is the water-land transition mode. Analysis of this interface of "twilight zone" mode is extremely complicated, involving consideration of both hydrodynamical and terramechanical factors. Investigation of many actual field problems has demonstrated that the transition phase, particularly egress, is usually the most difficult element of the entire stream-crossing maneuver; hence this complication cannot be avoided.

Another area in which the current efforts represent only a scratch on the surface of the problem is that associated with the determination of environmental attributes. It has become apparent that complete quantification of world-wide stream properties in sufficient detail for vehicle performance evaluation cannot possible be achieved by direct measurement within the scope of any reasonable study, nor is the military really

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interested in the characteristics of every stream in the world. Therefore, an approach toward categorizing waterways on the basis of available climatic, geological, and other existing environmental data has been initiated as part of the study, so that those of military interest may be studied.

It is worth repeating here that the present work is by no means regarded as a finished product. Many of the relationships which are presented should be considered as no more than reasonable hypotheses (others, of course, are advanced with considerably more confidence -- the distinction is always clearly drawn in the accompanying discussion). These hypotheses must be validated and, if necessary, modified on the basis of carefully controlled experiments. Much additional research in the various problem areas and a major effort to coordinate the various facets into a comprehensive systems analysis is required before the kind of evaluation-scheme envisioned as the long-term goal of this study can be achieved.

This document (Vol. III) represents a part of the entire multi-part study to which this foreword is an over-all introduction. Volume I is devoted mainly to the fully water-borne situation. Volume II is concerned with water-land transition.

INTRODUCTION TO VOLUME III

The natural physical environment of a river system includes geology, climate, soils, vegetation, and many other similar elements. Some of these are whole branches of sciences such as hydrology and meteorology, and they cannot be considered fully in a report of this kind. Only an overview, in the form of material extracted from published works, is attempted, to help meet the need for identifying vehicle mobility problems associated with riverine areas. Knowledge of the nature, magnitude, and frequency of stream occurrence, and knowledge of climate, is required not only as an aid to the design of vehicles but also as an aid in determining the ability of a vehicle to traverse a particular terrain.

Implicit in the vehicle stream-crossing problem, of course, is the need for a method of predicting the nature of inland waters and neighboring terrain, from available climatic and geological data. In addition, there is a need for a properly validated set of vehicle performance equations for application to water crossing, slope climbing, and other problems related to the predicted environmental factors.

Needless to say, the available literature on environment is voluminous -- but deficient in the kind of data that would answer the basic question, "Can this vehicle cross this waterway?" This report is therefore presented from a highly generalized, possibly oversimplified, point of view, to establish a conceptual framework within which subsequent research needs can be specified. The equations that are presented have been checked out in but the crudest fashion, in many cases only by the individual who derived them. Hence they are all open to question until validated by competent researchers.

For a more detailed explanation of some of the terms utilized in this report, the reader is directed to Manual No. 43 of the American Society of Civil Engineers, "Nomenclature for Hydraulics" (1962), and to the Coast and Geodetic Survey Paper 1541-A, "Water Supply" (1960).

Chapter 1

EVOLUTION AND DELINEATION OF A RIVER SYSTEM

SOURCES OF SURFACE STREAMS

The waters that eventually become part of a river derive primarily from the precipitation of atmospheric moisture. Rivers may be fed and maintained by direct surface runoff of rainfall, springs, or other ground-water seepage, and snow melt. Surface runoff usually starts as a sheet of water, but it does not progress far before obstacles, such as vegetation and terrain irregularities, divide it into rivulets. The latter carve out minor gullies and form rills and brooks, which comprise the "headwaters" of a river. These tributaries, following the topographic slope, join the main streams and ultimately empty into the ocean. Along the way, the kinetic energy of the water, aided by chemical and thermal action, erodes the banks and bottoms of the rivers, transporting the sediment farther downstream. Upon reaching the ocean, the water is returned to the atmosphere by evaporation. Maritime air masses carry the evaporated moisture back over the land in vapor form, where it is cooled and precipitated, completing what is known as the "hydrologic cycle" (Fig. 1).

On the other hand, should surface runoff encounter rough ground, forest litter, or topographic basins, water may be trapped temporarily, creating swamps and lakes. Standing water either evaporates into the atmosphere or percolates into the ground. In the latter case, the ground water may be brought to the surface by capillary action, where it is returned to the atmosphere by evaporation or transpiration by plants, or it may descend to the water table, eventually emerging at lower elevations as springs or seepages into rivers and lakes.

Snow melt is another source of water for surface streams. In the mountains and in the middle and upper latitudes, snowfall comprises a significant portion of the winter's precipitation. Consequently, the

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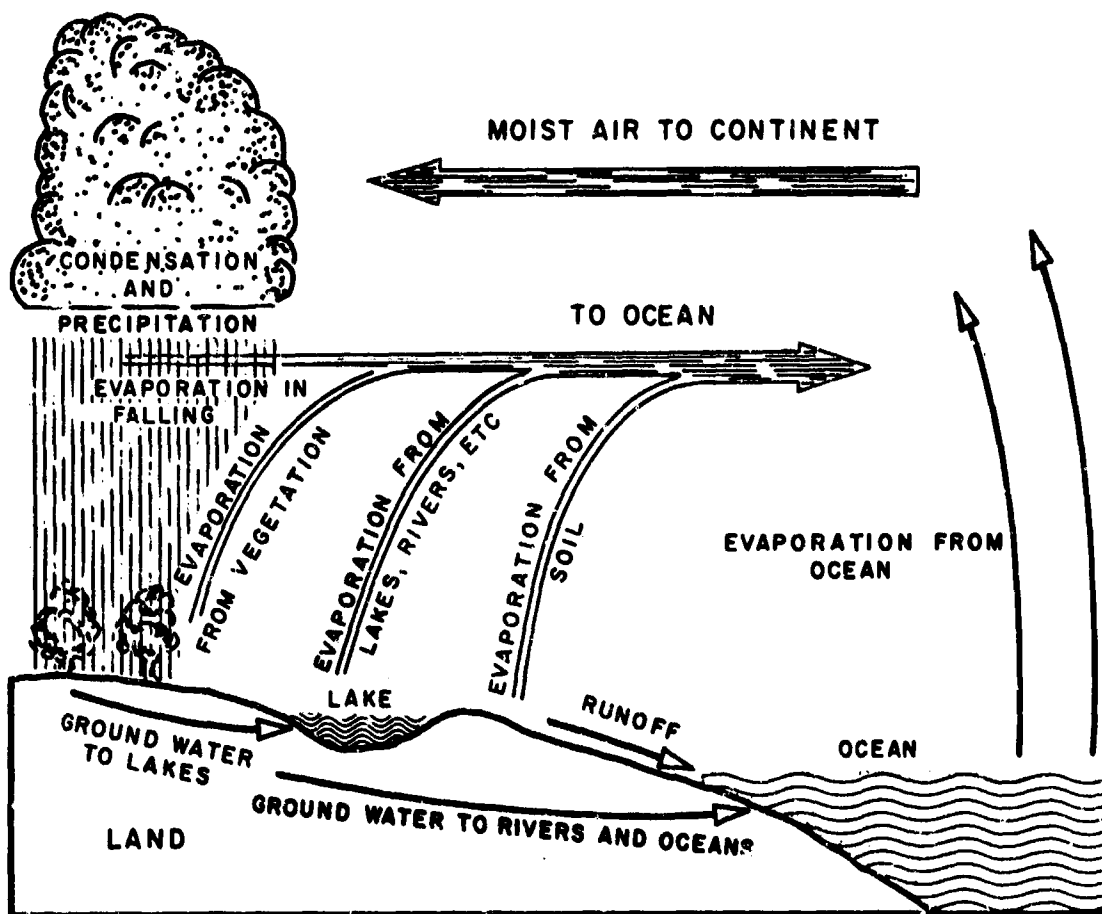
FIGURE 1.   THE HYDROLOGIC CYCLE

| Dendritic | Trellis | Radial | Centripetal |
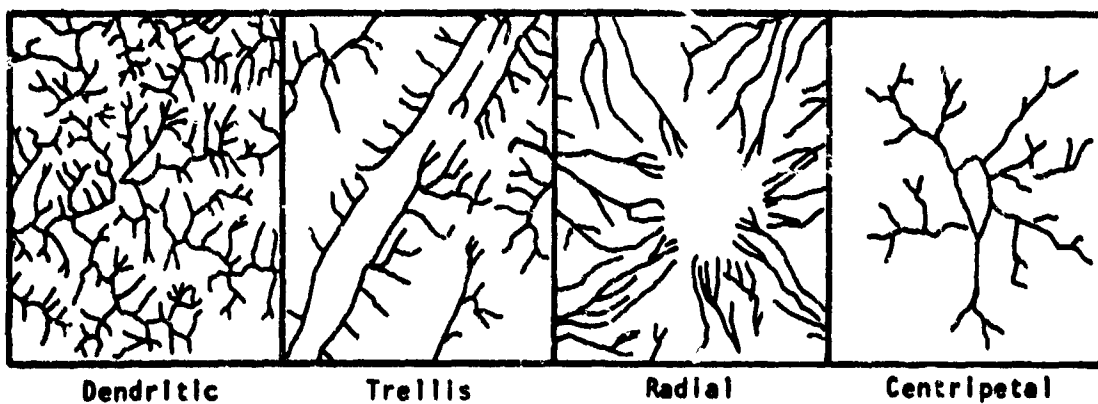
FIGURE 2.   DRAINAGE PATTERNS OF RIVERS

moisture in its frozen state is held in storage until the spring thaw
arrives. Release of the snow melt often coincides with the spring rains,
when the upper ground layers are still frozen. This combination of events
usually results in a combined water runoff volume much in excess of the
drainage system's capacity, and causes high water levels, fast stream
currents, and frequent flooding.

STREAM PATTERNS

It has been noted, in the preceding section, that the headwaters of a
river system empty into the major tributaries, and that these, in turn,
join the main stream. Their relative orientation and over-all distribution
typically become arranged in what is referred to as a "stream pattern."
Stream patterns may be classified into eight principal types (Fig. 2), viz.:
dendritic, trellis, parallel, annular, radial, centripetal, rectangular,
and aimless. The development of a particular pattern is determined more
or less by the underlying geologic structure and climatic regime of the area.

A dendritic pattern describes a river system in which the relative
position of the main stream and its branches forms a figure very much like
the veins in a tree leaf. This type of pattern develops on horizontally-
lying sedimentary strata or homogeneous bedrock, such as granite, where the
only natural control is the original topographic slope. The master stream
flows down the regional slope, and its major tributaries tend to take the
downslope direction as they approach from both sides. This kind of drainage
pattern is perhaps the most widespread and may be found on coastal plains,
interior plains, plateaus, certain hill regions, and some mountains.
Glacial drift, which is non-homogeneous in its component particles but is
broadly homogeneous in structure, may also develop a dendritic drainage
pattern.

A very different drainage pattern is the trellis type, in which the
larger streams are roughly parallel. This pattern develops in an area of
folded or tilted rock strata. Weaker beds yield rapidly to erosion and
form the valleys containing the larger streams; stronger beds stand out as
linear ridges between valleys. The main streams have a more or less

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parallel orientation, receiving their short, right-angled tributaries from the adjacent ridges. Some streams may break through the ridges in "water gaps," to give a roughly rectangular aspect to the stream pattern. The region in the world most notable for its trellis pattern is the Appalachian Ridge and Valley Province, which stretches from Northeastern Pennsylvania southward to Alabama. The folded sedimentary formations usually include shale and limestone (which are weak under the prevailing humid conditions and thus form the valleys) and sandstone, conglomerate, and quartzite (which are strong and form the parallel ridges).

There are several variations or special forms of the trellis pattern. In areas of homoclinal dips, the streams flow in troughs between layers of dipping sediments, producing a <u>parallel</u> drainage pattern. Where a dome has been uplifted through layers of sediment and has been maturely dissected, drainage follows circular courses, cutting into the outcrops of the weaker sedimentary belts and forming an <u>annular</u> drainage pattern.

On young dome mountains, volcanoes, and prominent peaks, drainage is away from the central point or area. Streams flow downslope in an outward direction, creating a <u>radial</u> pattern. Structural basins also have a radial drainage pattern, but streams flow in the opposite direction, toward the center. Consequently, this type of stream pattern is called <u>centripetal</u>.

Somewhat similar in appearance to the trellis network, but evolving under geologic conditions other than those occurring in the differential erosion of stratified rocks, is the <u>rectangular</u> stream pattern. The pattern develops with the occurrence of structural joints in rock. Such joints are found at rock folds, intrusions, and regions of faulting. They provide ready-made channels for drainage. The very nature of joint formation (i.e., the development of cross joints along longitudinal joints) and the tendency for fractures in intersecting joint sets to be perpendicular to one another, causes the surface drainage to assume a rectangular pattern.

Another drainage pattern, which may be called <u>aimless</u>, is found in young glaciated plains. The irregular rolling surface of the drift deposits, as left by the glacier, contains basins and swells in haphazard arrangement. Rainwaters first made ponds or swamps in the closed basins, which then overflowed their low rims into other depressions. The resulting

streams may wander back and forth, connecting the remaining ponds and
swamps, but showing in their pattern no evidence of control either by
underlying rock structure or regional slope. Nevertheless, the aimless
pattern of the drainage characteristics reveals its origin and associates
it with glaciation.

Chapter 2

PHYSIOGRAPHIC CLASSIFICATION

The development of the general stream pattern is controlled by the underlying bedrock and structure in the area. As stream valleys develop, the surrounding surface features become the product of interaction between the local geology and the prevailing climate. The resultant topographic formations are thus directly related to the surrounding set of natural conditions, in the creation and orderly development of landforms. The interrelationship is part of a systematic scheme embracing the whole world, and permits identification, differentiation, and classification of types. However, if one accepts the premise that only a limited number of landscape types exist in the world, and that they can be classified, then the basis for analysis and storage of environmental data becomes feasible, and this makes it possible to classify an unknown landscape by matching its characteristic features with those of the known types.

According to Lobeck[2], relief features occur in three different sizes or orders. Those of the "first order" are the continents and the ocean basins. The continental areas encompass relief features of the "second order," e.g., mountains and plains, which are called "physiographic provinces." Finally, physiographic provinces are composed of relief features of the "third order," namely, landscapes that can usually be comprehended in one glance. It is obvious that, because of their somewhat subjective definition, the size and shape of a relief feature will sometimes differ in detail, depending upon the authority quoted. Nevertheless, this scheme can be used to identify, on the different continents, certain regions whose critical characteristics are similar.

The principal characteristics used for identification are:

(a) Climate   (d) Terrain

(b) Soils   (e) Drainage pattern

(c) Vegetation   (f) Cultural modifications

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Of these, only the first three are discussed here in any detail. In
applying these physiographic characteristics to the study of riverine
environments, it should be pointed out that, although the flow of all the
principal rivers of the world is generally known, there is little detailed
information available for characterization, correlation, and extrapolation.
Measurements of precipitation, immediate runoff, infiltration, and
evaporation have been made, but only at widely scattered stations. Even
at these locations, the records may not be continuous or cover a long
period of time.

CLIMATE

The climatic factor is one of the most influential, if not the most
important, element in the natural environment. It determines, to a
significant degree, the development of all the other environmental factors.
As a consequence of this relationship, the prediction and identification
of many unknown characteristics is often possible if only a few of these
factors are known. The late Vladimir Koeppen of Austria applied this
principle in 1918, when he presented his famous climatic classification
based on the world's floral (natural vegetation) distribution. Two
important modifications and refinements to Koeppen's system have since been
developed and are described below.

The Holdridge System of Climate Classification

Research being conducted under the auspices of the Advanced Research
Projects Agency (ARPA) and the Army Research Office (ARO) indicates the
fundamental correctness and unprecedented organizational capabilities of
the Holdridge system of World Life Zones[3] for the classification of
climates of the world (Fig. 3). This life zone system is basically
related to vegetation, and quantifies (with some manipulation) the
long-recognized phenomenon that evapotranspiration (evaporation +
transpiration) varies with rainfall, temperature, and vegetation. Since
this system relates vegetation to rainfall and temperature, specification
of only the latter two terms is basically sufficient. Thus, the Holdridge
system permits the first-order identification of climate in quantitative

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FIGURE 3. CLASSIFICATION OF WORLD LIFE ZONES BY L. R. HOLDRIDGE

(A) Tbio = mean of unit-period temperatures with substitution of zero for all temperature values below 0°C and above 30°C, respectively (formula is tentative, pending further investigation)

(B) In tropical subalpine only

terms. Where meteorological data for an area are lacking, the area's
climate may be identified by ground recognition or air-photo interpretation
of the existing vegetation. Once the vegetation is known, it becomes
possible to use Holdridge's Classification Chart to stipulate the
corresponding climatic conditions in the region.

Of greater importance to this riverine study is the fact that rain
water not lost by evaporation from free water surfaces, or absorbed by
vegetation (a really significant loss), will form the streams and rivers of
the region. In other words, it should be possible to determine the local
drainage characteristics if the amount of rainfall that runs off the ground
surface and the amount of rainfall that percolates through the soil to
establish the ground-water regime (and, eventually, the issuing creeks and
streams) are known.

Once a stream "environment" has been computed (or observed) for a
particular world area, similarity can be presumed for other world areas
having similar climate, with suitable local restraints on true comparability.
Thus, it is this system which has the most potential for forming the basis
of efforts to relate environment to the nature of streams and other directly
applicable aspects of off-road conditions.

The Thornthwaite Precipitation-Effectiveness Index (P-E)

Another method which would be useful in predicting the nature of
surface drainage is the Thornthwaite Precipitation-Effectiveness Index.
This index is a measure of the availability of moisture to vegetation, which
depends on the amount and distribution of both precipitation and evaporation,
with the latter, in turn, depending on variations of temperature and wind
movement.[4] The exact rational formula for the P-E Index, $\hat{I}$, is

$$\hat{I} = 10 \sum_{12} \frac{P}{E}$$

where P is the average precipitation for each month and E is the average
evaporation for each month. The P-E Index is therefore a dimensionless
ratio. An empirical formula that is an approximation to $\hat{I}$, when no

evaporation data are available, is

$$\hat{I} \; = \; 115 \; \sum_{12} \left(\frac{P}{T - 10} \right)^{1.11}$$

where T is the monthly average daily temperature.

Thornthwaite divided the range of values of $\hat{I}$ as follows:

Characteristic Vegetation	$\hat{I}$
Rain forest	≥ 128
Forest	64 – 127
Grassland	32 – 663
Steppe	16 – 31
Desert	≤ 15

Multiple correlation analyses have shown that valley-side slopes and drainage density are related to climate and to properties of mantle and vegetal cover as measured in the field.[5] It has been found that as the climate becomes more humid (all else being equal), the infiltration capacity increases and also the P-E Index. With greater infiltration and interflow, the ratio between surface runoff and channel flow decreases, so that the volume of water available for valley-side erosion is reduced. Channel flow will deepen the valley more rapidly, resulting in steeper valley slopes. Conversely, gentler slopes are produced with an increase in surface runoff frequency-intensity and wet soil strength. As shown by the multiple correlation analyses, the density of a drainage pattern is directly affected by the percentage of bare area and the runoff frequency-intensity, but varies inversely with the ground's infiltration capacity and, thus, the P-E Index. These analyses substantiate the theoretical observations of Gilbert, Davis, and Johnson, as well as Horton's infiltration theory of erosion.[6] Since the primary controls of the topographic texture are lithology and climate, acting through the agency of secondary surface properties, any accidental changes in the secondary controls (unrelated to climatic changes) will quickly alter the drainage density to a value other

than that expected from consideration of climate and lithology alone.

SOILS

The classification of soils has received considerable attention in connection with both vehicle and agricultural studies. In such studies, the term "soil structure" is used to refer to the physical arrangement of the soil particles, which influences the movement of soil water and the growth of vegetation. Many soil-structure terms are described in detail in the Soil Survey Manual of the U. S. Department of Agriculture. Blocky, nut, or crumb structures involve irregular clods of fragments of varying sizes; platy structure consists of thin sheets with a property of splitting; granular structures are much like crumbs; prismatic and columnar structures consist of vertical columns; dune sands have "single-grain" structures.

The term "soil texture" refers to the sizes of the constituent soil particles, and soil type is classified on the basis of particle size distribution (percent by weight), as shown in the following table:[7]

Soil Type	Sand	Silt	Clay
Clay	15%	15%	70%
Clay loam	33	33	33
Silty clay loam	10	60	30
Silt	5	90	5
Silt loam	22	63	15
Sandy clay	50	10	40
Sandy loam	70	20	10

Perhaps one of the most interesting aspects of soil classification, in the context of this report, is "soil profile," a knowledge of which can be useful in studies of stream banks (especially the banks of gullies, as we can see in Fig. 4).

Of all the soil types, only the podzols and tropical latosols are mentioned in the literature as having characteristics which affect river

Soil Characteristics	Idealized Fully Developed Cross Section	Cross-Section Erosional Process
COHESIVE CLAYS AND SILTY CLAYS (Usually found in lake beds, marine terraces and clay shale areas)		Original Surface Developed Gully Low, uniform gradient
MODERATELY COHESIVE, WEAKLY CEMENTED SAND-CLAYS (Occur in coastal plains and many bedrock areas)	Weathered soil profile with some clay Loose soil or rotten rock	Original Surface Developed Gully Compound Gradient
MODERATELY COHESIVE SILT (Primarily loess and alluvial silt deposits; also fine volcanic ash falls)		Original Surface Fins and pinnacles near head-end Compound Gradient
NON-COHESIVE GRANULAR MATERIALS (Often found in terraces and outwash plains)		Very steep gradient = coarse material, few fins Short, steep, uniform, gradient = well-graded mixtures

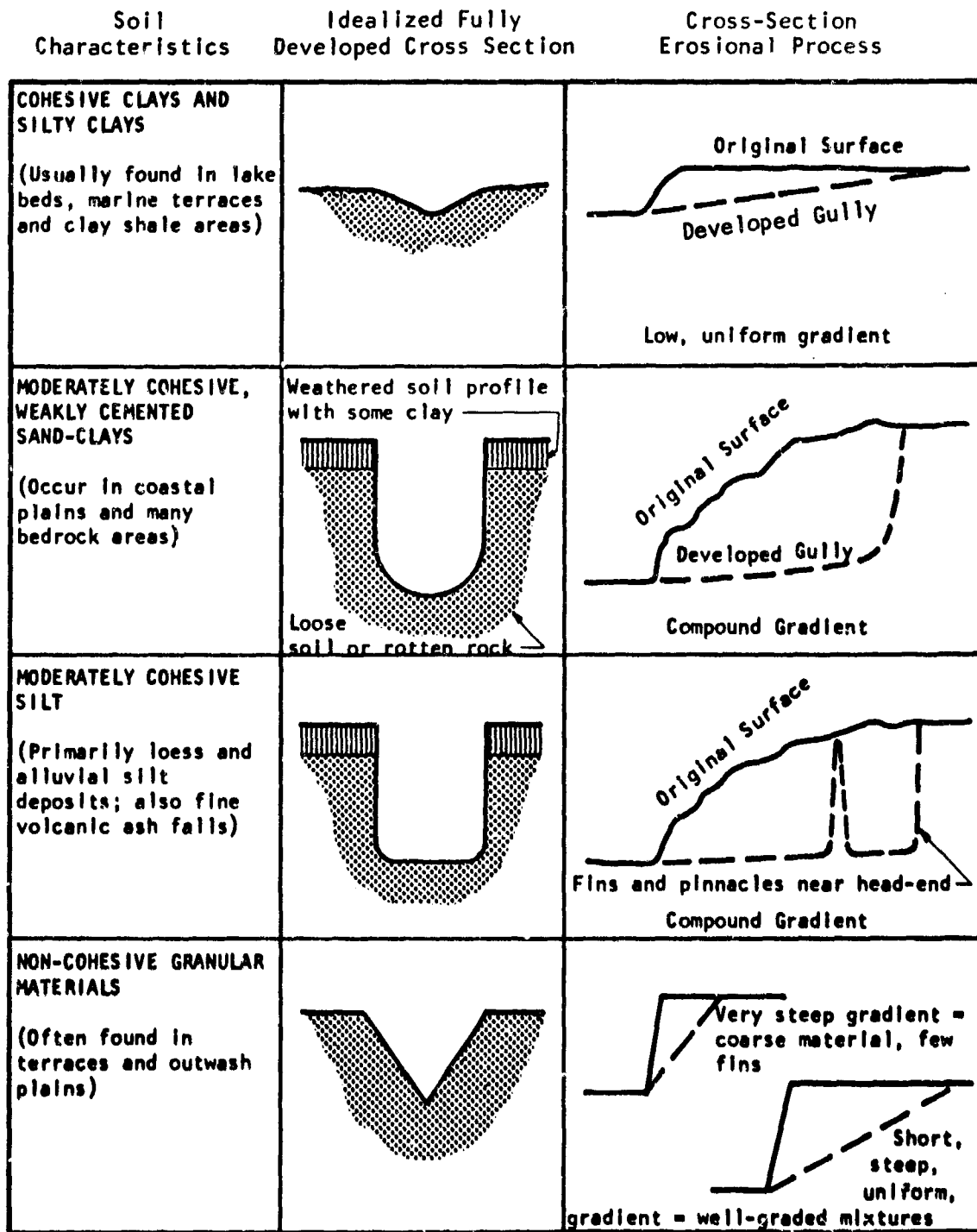FIGURE 4. GULLY PATTERNS. GULLY FORMS ASSOCIATED WITH SILTY CLAYS AND CLAYS, SILTS, SAND-CLAYS, AND GRAVELS AND SANDS. THE COHESIVENESS AND PARTICLE-SIZE OF THE SOIL INFLUENCE THE PLAN, PROFILE, AND CROSS SECTION OF A GULLY. THE SOLID LINE REPRESENTS THE ORIGINAL LAND PROFILE AND THE DOTTED LINE THE PROFILE AFTER THE GULLY IS FORMED. FINS AND PINNACLES ARE RESIDUAL STRUCTURES CONSISTING OF MATERIAL RESISTANT TO EROSION[8]

formation. In the case of the podzols, which develop under cool or cool-humid conditions, particularly under needle-leaf forests, iron may be precipitated below the surface, to form hard, rusty crusts. In the case of the tropical latosols, which are found in the humid tropics, water leaches out basic soluble substances and most of the silica, leaving surface material rich in iron and aluminum oxides and hydroxides.

While the characteristics of a lateritic soil are changing, the banks of a stream flowing through that soil are undergoing related changes. As a lateritic soil matures, it is better able to stand on steep slopes, since it is commonly well drained and ultimately low in shrinkage and plasticity. Therefore the banks of the stream flowing through this soil may be steeper than those of a stream of similar capacity flowing in non-lateritic soils. In general, the most highly laterized soils exhibit the least surface-drainage development and the least gully erosion.

Although the soil characteristics of the surface layers do tend to be relatively uniform in the case of well-advanced laterized materials, the various strata (mottled, pallid, cemented, and weathered zones) are encountered as depth increases, and soil characteristics change greatly. For intermediate soils where laterization has not gone very far, the change in soil characteristics at a shallow depth can be even greater. On the other hand, very young soils have very little soil-profile development; there is relatively uniform soil or soil over rock. This may be taken to mean that the degree of slipperiness or stickiness on an individual stream bank-cut can vary according to the depth of the cut and the type of soil found at any given vehicle crossing site. Where there are steep bank cuts, the change in stability from surface to subsoil, and to weathered rock and bedrock, is therefore significant.

Many soils in the tropics have not gone through the laterization process far enough to change their properties significantly. These would include most of the soils composed of newer materials transported and deposited by streams, such as those on flood plains and deltas. They can be recognized on aerial photos by their characteristic forms.

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VEGETATION

Climate, rather than soil, is considered the strongest factor in the distribution of vegetation. Temperature, precipitation, sunlight, humidity, and wind -- all elements of climate -- form a complex of conditions within which the plant must grow. Each plant type generally grows best at one temperature level, but will tolerate temperatures within a certain range above and below the optimum. Sufficient soil moisture must be available to the roots during the period when transpiration is most active. Short grasses grow during the warm season and need water, but during the winter or dry season they require very little moisture. And during the growing season some deciduous trees transpire large amounts of moisture from their leaves, yet very little after they shed their leaves. Humidity and wind affect the rate of transpiration, and also evaporation from the soil. Evapotranspiration decreases as relative humidity rises, but increases directly with increasing wind velocity. Tall trees may suffer greater losses in transpired moisture than grasses and other low plants, because air movement increases with height above the ground. Sunlight is also very important. In high latitudes, where summer days are of extremely long duration, the growth rate of certain plants is very rapid during this short frost-free period.

It is possible to recognize certain broad vegetation groupings that form a pattern of major world belts, some tropical, some in intermediate latitudes, and some in the cold regions. Temperature is a major control of vegetation groups, along with precipitation. For example, rain forest and deserts are found along the same latitude, because of the differences in precipitation.

The four major groups of vegetation types are the forests, grasslands, desert associations, and tundras (cold heaths or meadows). The greatest variety occurs among the forest types, which include tropical rain forests, lighter tropical forest and thorn forest, Mediterranean scrub forest, various temperate broad-leaf forest types (mainly deciduous), various needle-leaf forest types of the middle latitudes (mainly evergreen), and wet forests such as the mangrove swamp.

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Insofar as plants are concerned, soil is of second importance to
climate. Because of this strong climate-plant relationship, the Holdridge
system (Fig. 3) is a valuable tool in predicting the gross characteristics
of vegetation for any specified area.

The character of aquatic plants is closely related to river-bed
composition and to stream velocity. The larger plants, for example, cannot
be expected to thrive in a rocky or pebbly river bed, but they will grow
well in silt. This means that aerial photography might be helpful in
determining the composition of a river bed. However, the character of a
stream bed can be altered by drastic changes in discharge and in flow
velocity, with accompanying changes in stream vegetation from year to year
or even from month to month.

LITHOLOGY AND TECTONIC HISTORY

It is almost meaningless to consider isolated elements of environment.
The interaction of geologic and climatic elements with prevailing physio-
graphic processes produces corresponding variations in vegetation growth,
soil formation, runoff, soil creep, etc. It is generally agreed that the
underlying bedrock and geologic structure form the basis for drainage
density and pattern in a region -- the lithology by providing the potential
amount of clay in the soil and thus affecting infiltration capacity and
soil strength, and the structure by prescribing frequency of outcrop. It
must be emphasized, however, that the climatic elements prevailing in the
region will determine the ultimate drainage characteristics. In other
words, should the same rock formations be exposed in different parts of the
world to different climatic influences, the resultant drainage would
undoubtedly vary in each region.

CULTURAL MODIFICATIONS

Human activity disturbs the equilibrium of any stream or river,
usually not only along the flood plain (the usual location of towns and

cities), but at many more places in the drainage basin.[*] This disturbance
has two possible effects: first, through the abuse of natural vegetation-
cover in the drainage basin, the production of sediment in the area can be
increased, augmenting the stream load and aggrading the channels; second,
through soil conservation, sediment production and stream load can be
decreased, increasing flow velocity and degrading the stream beds. Other
examples of human interference are:

(a) The modification of river banks (the building of levees,
the grading of banks, and the construction of roads and
road foundations that run parallel to river banks;

(b) The building of canals

(c) The construction of irrigation systems

(d) The construction of excursionary channels to bypass rapids

(e) The construction of inter-river connections

(f) The construction of dams

Wherever civilized man concentrates his efforts to build centers of
population and to develop natural resources for the use of those centers,
the equilibrium of the streams in the vicinity will be affected.

DRAINAGE

The development of a stream and its tributaries usually leads to a
widespread, interconnected drainage network. The stages of development of
a river system are listed below:[8]

(1) Initial. A wide, shallow, fast-flowing stream marks the
beginning of the network.

(2) Youth. Valleys soon begin to develop. There are few
tributaries, and the gradients are commonly steep.

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[*] Stream equilibrium exists when the consistent changes in stream-bed
profile are so small that they cannot be measured over a period of ten
years.

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(3) Mature. Erosion has continued to the point where streams have nearly reached baselevel (strictly, the downward limit of erosion imposed by the sea), where flood plains have begun to develop, where land surface is in slope, and where the number of tributaries is at its maximum.

(4) Old age. Erosion has brought the tributaries near baselevel, a flood plain is dominant, divides are removed, valleys are merging (reducing the number of tributaries), relief is small, and the drainage is poor.

Within the drainage system, a "fine-textured" drainage area is one which develops on impervious rock or soil layers, resistant to the movement of water through them. In this case, subsurface drainage is greatly retarded. A "coarse-textured" drainage area develops on permeable bedrock, which permits the passage of ground water with ease. In general, straight, braided (interlacing) river channels may indicate unstable conditions in coarse materials, whereas meandering channels are usually indicative of stable conditions on fine materials. However, both braided and meandering patterns may be found together, especially in Alaska.

Chapter 3

SOME FORMATIVE ELEMENTS IN THE RIVER SYSTEM

No two rivers are exactly alike, because the behavior of each is controlled by so many independent and interdependent factors. Yet the behavior of one particular stream may have a significant bearing upon the success or failure of a military operation, for it can hinder the operation if its waters are deep enough or turbulent enough to threaten the safety or the operation of crossing vehicles, or if its banks cannot be negotiated by these vehicles.

To characterize stream types for military purposes, great effort must be made to collect and study the open records for all areas of significance, selecting available data in the form of stream-flow measurements, meteorological observations, channel surveys, design information on dams and reservoirs, soil and sediment characteristics, channel stability, etc. The value of stream-flow records cannot be overemphasized; these frequently represent many man-years of observation and analysis.

By combining the known facts of remote environments with field measurements and studies of streams in comparable but accessible areas, it should be possible to predict the characteristics of these important unknown streams. A discussion of some of the physical and hydraulic factors that must be investigated is presented below.

RUNOFF

Continental water bodies represent surplus water that accumulates over and above (1) the amount used by plants and animals, (2) the amount that returns to the air as the result of evaporation, and (3) the amount needed to replenish the empty storage spaces in rocks and soils. Effective runoff can be considered to be the difference between precipitation and evapo-transpiration. Figure 5 illustrates the effect of slope, surface materials, and temperature on surface runoff. Figure 6 illustrates the relation of

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STEEP SLOPE - RAPID RUNOFF   IMPERVIOUS-RAPID RUNOFF   HOT-RAPID EVAPORATION

CLAY OR FROZEN SOIL

PERVIOUS - MODERATE RUNOFF

SILT

LITTLE SLOPE - LITTLE RUNOFF   COLD - LITTLE EVAPORATION

EXCESSIVELY PERVIOUS-
LITTLE RUNOFF

RAPID SUB SURFACE DRAINAGE   GRAVEL

(A) SLOPE   (B) SURFACE MATERIALS   (C) TEMPERATURE
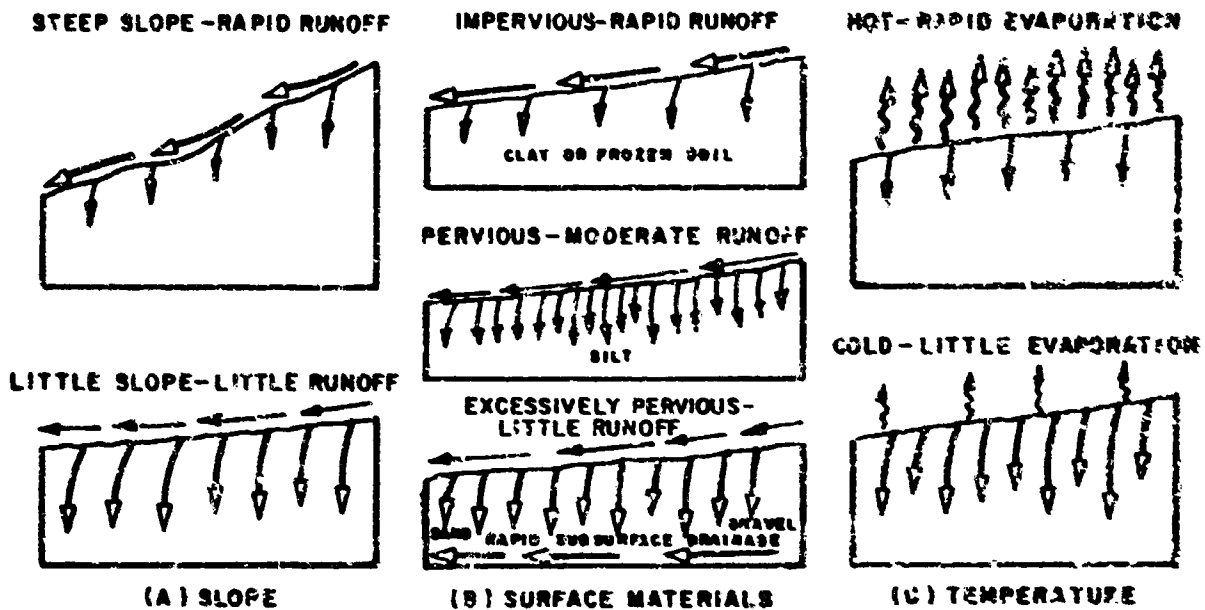
FIGURE 5.   FACTORS INFLUENCING THE MOVEMENT OF SURFACE WATER INTO THE GROUND

WATER TABLE DURING
WET SEASON

SPRING   WELL HILL

LAKE

SATURATED ZONE   WATER TABLE DURING
DRY SEASON   SATURATED ZONE
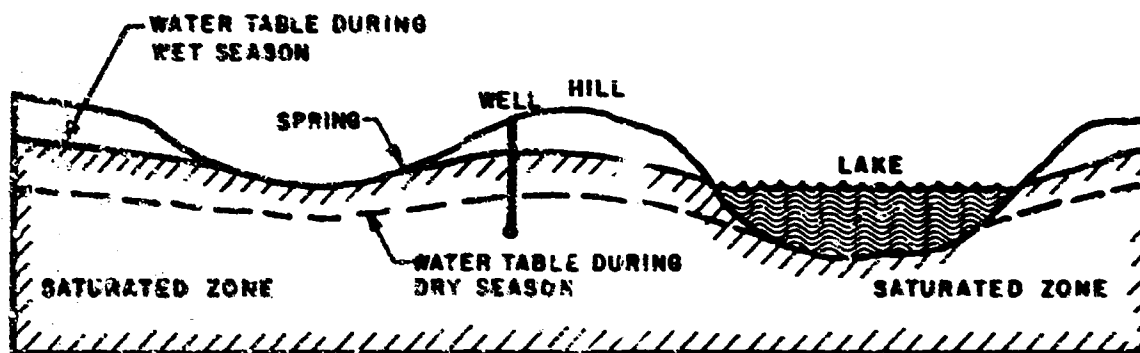
(A) POSITION OF THE WATER TABLE

WATER TABLE IN FINE
TEXTURED MATERIALS

STREAM

WATER TABLE IN COARSE
TEXTURED MATERIALS

WATER LOSS TO GROUND

SATURATED ZONE   SATURATED ZONE
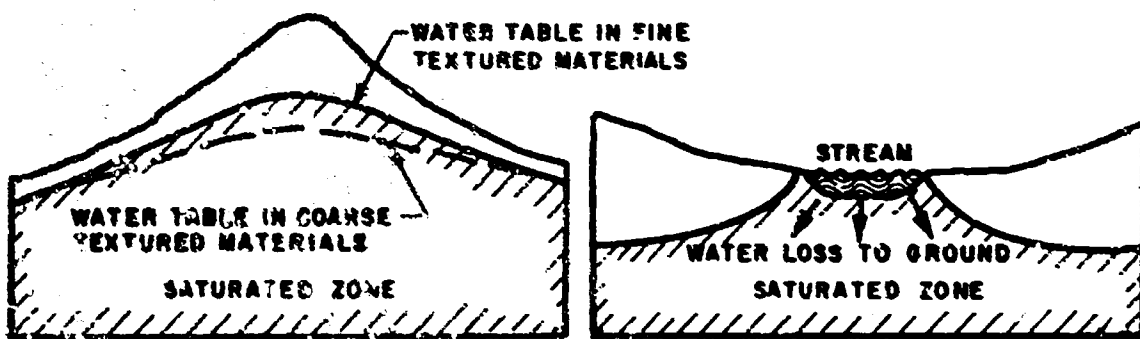
(B) MATERIALS AND THE WATER TABLE   (C) INFLUENT STREAM

FIGURE 6. DIAGRAM OF A WATER TABLE AND ITS RELATION TO TOPOGRAPHY AND
SURFACE MATERIALS; IN (C), THE STREAM LIES SOMEWHAT HIGHER THAN THE WATER
TABLE ON EACH SIDE AND HENCE LOSES WATER TO THE GROUND BELOW

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water table to topography and surface material as it affects runoff.*

The absence of drainage is significant and may be due to one of the following conditions:

(1) A small watershed. There is insufficient surface for the development of a runoff pattern.

(2) Granular material. Surface drainage is not well developed because of permeability of the soil, as in some gravel terraces. Tributaries from adjacent land often end abruptly on the border and find their way underground.

(3) Porous rocks. Surface water percolates down to the water table through cracks and cavities.

(4) Soluble rocks. In limestone regions, sinkholes are often developed that lead underground to subterranean passages.

(5) Water tables. In flood plains, lake beds, and lower coastal plains, the water table is often high and the area level.

Drainage patterns are more fully classified, and terms are defined specifically, in Table 4 of "Forecasting Trafficability of Soil."[9] Chapter 5 of this report contains an analysis of stream size distribution and a discussion of the relationship of drainage to the depth, width, and velocity of a stream.

VELOCITY

Stream velocity varies with changes in rainfall, groundwater, discharge, load, gradient, and many other factors. Velocity increases when the flow enters a narrow section of channel. But as banks cave in, the channel section becomes wider and shallower, and velocities near the side slopes diminish until they are too low for further erosion. This reduction of velocity is attained both through a lowering of the mean velocity in the river because of a less efficient cross section, and through a lowering of the ratio of side to mean velocity because of the change in the shape of

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*For analytical discussion of runoff, see Chapter 5.

the cross section. Where the bank material is coarse sand, the bank will
be uncohesive and erode easily, and the channel will become relatively wide.
If the bank material is a fine sand, clay, or silt, it will be cohesive
and will retain steep slopes, and the channel will remain relatively
narrow.

It should be remembered that the flow velocity at a given station
increases at a greater rate with greater discharge than does width, because
of increasing depth. At conditions greater than bankfull discharge, the
trend is reversed and velocity actually decreases while the width increases
greatly. With maximum discharge, all the coarser grades of debris are in
transit. With lessening discharge, the coarsest sediment is dropped, chiefly
in the deeps, because here is where the change in bed velocity is the
greatest. At the same time the coarsest of the suspended load escapes from
the body of the stream and joins the bed load. Soon the process becomes
selective; the finer part is carried on, while the coarser remains. Thus
the shallow channels on the bars become paved with particles that the
enfeebled currents are unable to move. These movements are important to
studies of channel stability.

The maximum speed of a current usually occurs in what is called the
navigable passage or channel, which is usually at the deepest part of the
river. Where there are rapids, this passage is usually in the center of the
river, but at bends the passage shifts toward the washed-out bank. The
swift current is, of course, more noticeable in a narrow, straight river,
or during floods. The approximate surface speed of a river current is
easily measured with a piece of board allowed to float between two shore
points a measured distance apart. Of course, there is a change in velocity
with both depth and transverse position in the stream.

Velocity changes are also discussed in connection with stream deposits
(Chapter 4) and with fluctuations in discharge (Chapter 5). As already
noted, the interrelationship of velocity, depth, width, and drainage area
is presented in Chapter 5.

TURBULENCE

Turbulence is a factor in causing the relatively large, coarse material in a river's "bed load" to roll, bounce, and saltate[*] near the bottom of the river, while keeping the "wash load," composed of relatively fine material, in suspension. The finer particles in a suspended load may be fairly evenly distributed over a vertical plane, whereas the coarser particles usually have their largest concentration at the lower levels of flow.

Rivers with a greater depth of flow than others will have the greater turbulence and can be expected to have greater concentrations of suspended sediment (if we assume that discharge, hydraulic roughness, velocity, etc., remain the same). When the load of sediment is smaller than a river's capacity, the river will pick up material from its bed through turbulent motion. This movement of bed load is important to studies of stream-channel stability.

STREAM PROFILE

The slope of a river bed is, of course, an important factor in determining its behavior. Not all of the significant variations in slope occur along the upper course of the river where gradients are steep. The profile of a "normal" river from its origin to its mouth is concave upward, chiefly because, in the lower courses, slope is a function of sediment transport. The factors related to slope are listed below.

(1) The bed material, which mostly determines the slope of the river, wears down in size while it is being transported. Due to the abrasion, an increasing portion of the bed material becomes suspended sediment while the rest becomes smaller in size. Because of the increased load and greater deposition, the river gradient will be gentler farther downstream.

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[*]"Saltation" occurs when material moves with a surge in water pressure, and jumps to a new downstream position.

(2) The total flow of water becomes larger in the downstream
direction. If a tributary adds an equal flow of water
and sediment, sediment transport becomes more efficient,
and below the junction the river will flow at a gentler
slope than did the two rivers above. (A steady discharge
might increase the width between the banks of an incised
stream, but it would not be the same discharge that could
produce the breadth of a river's meander or the one that
could produce the river's slope.)

(3) In some drainage basins, the concentration of sediment
may decrease in the downstream tributaries (the upper
part of the drainage basin is normally the principal
source of sediment, whereas the whole drainage basin
provides runoff). Thus the concentration of transported
sediment in the main stream becomes smaller downstream,
and slope increasingly smaller.

(4) Many rivers are actively aggrading their lower courses,
that is, continuously depositing sediment over a long
section of river. This means that there is a gradual
decrease in slope, with this decrease of bed-material
load in the downstream direction.

There are many instances in which some of the above characteristics
are hardly noticeable or are non-existent. It may be, for instance, that
tributaries carry a relatively greater or coarser sediment load than the
main trunk. As a result, the main river will flow with a steeper gradient
below the junction and the profile may become concave downward. Another
cause for a concave downward shape of the river profile could be active
degradation in a section of river channel where the discharge remains the
same. The degradation will increase the sediment load downstream, and may
lead to an increase in slope in the downstream direction.

In an ideal channel composed of uniform non-cohesive coarse sand, the
bed profile would have a shape resembling a sine wave while the cross
section would look like a parabola. But this is an ideal situation seldom
provided in nature. Actually, most natural stream channels have trapezoidal
cross sections along straight reaches and are asymmetric at the bends.
(Fig. 7).[8,10] A rectangular cross section of the river becomes more
prevalent downstream, since width increases faster than depth and the
width-to-depth ratio tends to increase downstream.

CONCAVE BANK

DEEP POOL

SHALLOW
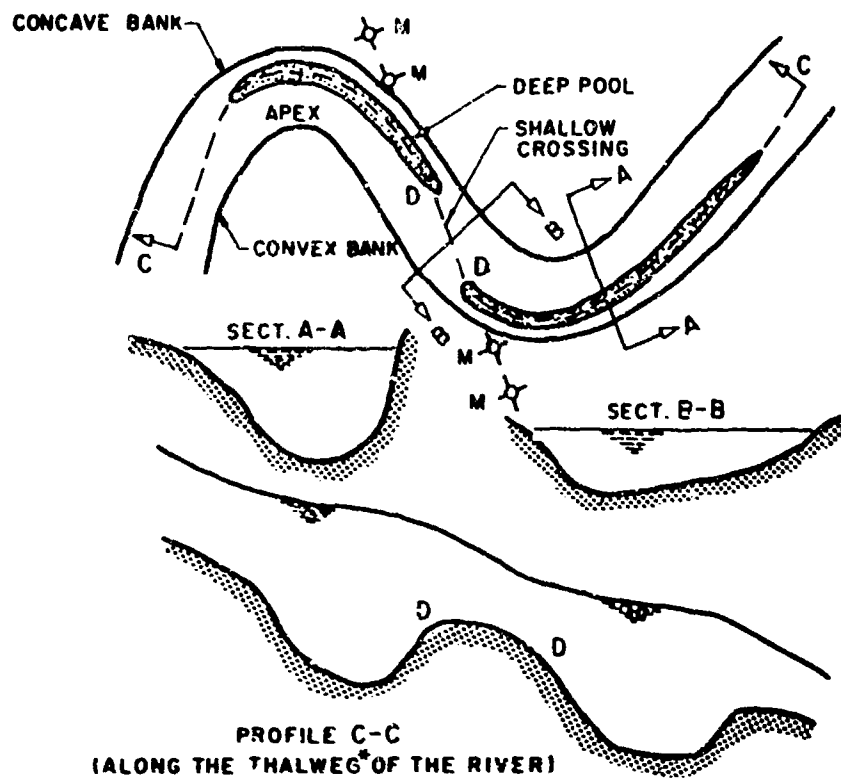CROSSING

APEX

CONVEX BANK

SECT. A-A

SECT. B-B

PROFILE C-C
(ALONG THE THALWEG* OF THE RIVER)

FIGURE 7.   CROSS SECTION OF A MEANDER

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* The lowest part of the stream bed.

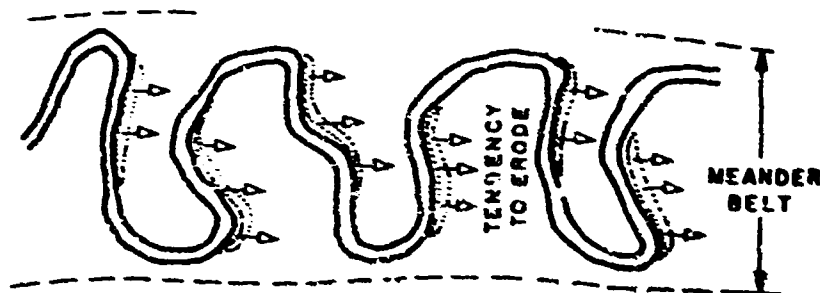

MEANDER
BELT

TENDENCY TO ERODE

FIGURE 8.   TYPICAL MEANDER BELT

The longitudinal profile of either a straight or meandering channel is often undulating with deeps and shallows alternating at distances equal to five to seven channel widths.[8] This phenomenon is more common in streams which have a greater variety of bed materials; it is caused by a tendency of larger grains to bunch together owing to the instability of the uniform flow of the discrete units. Figure 7 shows a cross-section of a meandering river, with the main current impinging on concave bends and causing an increase in depth.

Nor is the depth of flow uniform in the straight reaches of an alluvial river. It is more likely that pools, flow crossings, and sand bars will alternate in an irregular and continuously changing pattern. At places, the river may be wide and shallow; at other places it may be narrow and deep. Meander bends may be slowly migrating in a downstream direction. The discharge may be confined to one main channel, or it may be divided over several channels with islands in between.

DISCHARGE

Discharge is the rate of water flow through a channel expressed in units such as cubic feet per second or gallons per hour. It is related to variations in rainfall and runoff, and to variations in channel size and stream velocity.

Since discharge is the product of a waterway's width, average depth, and average velocity, it is possible to construct, quantitatively, the width-depth-velocity curves which will provide magnitude and frequency patterns for these parameters at any one point in a stream. If one relates field measurements, obtained from a study of nearby streams, to slope, relief, soil composition, vegetation, and size of the drainage area, it is usually possible to determine the time response of a stream, i.e., the time lag between the start of rainfall and the peak discharge.

Because of the variations in seasonal flow and in annual peak flows, it has been common practice to utilize one constant discharge which would produce the same effects as actual fluctuating discharges. This is called the "dominant discharge." At this discharge, equilibrium is most closely

approached and t'e tendency to change is least. It may be regarded as the
integrated effect of all varying conditions over a long period of time.
However, some typical features in river-channel formation would be lost if
the fluctuating river flows were replaced by a steady flow. In the normal
cycle of flow, during high-water periods, the bed within the bends is
scoured deeper, while at the crossings the level of the bed rises. During
the succeeding lower-water period, the bends are subjected to sedimentation
and a rise in the stream bed, while the crossings are scoured to lower
levels. This causes the route of strongest flow of a river to alternate
from one bend to another and from one shore back to the other.

An analytical discussion of fluctuations in discharge appears in
Chapter 5.

STREAM BANKS

No totally acceptable system is available to explain the soil composition
of river banks.* There is a noticeable lack of research in this area, and
most theory remains unvalidated by field tests. It is probable that the
upper course of a river would have banks constructed of materials (usually
stony or gravelly) basically similar to the surface rock across which the
stream flows. On the other hand, river banks in this region may contain
some traces of transported material deposited by floods. In the lower
courses of a river, where aggradation has begun, it is more difficult to
predict the composition of bank material, because the character of the
(more or less sandy) material deposited on the banks would be related to
the velocity of flooding water. As the velocity decreases, the heavier
particles are the first to be deposited on the banks. The nature of these
deposits would be dependent on the load introduced into the stream by its
tributary system. Leopoid[8] concludes that most particle sorting takes place
within the first few miles of a stream, and proceeds at a markedly slower
rate for the rest of the way, with a nearly uniform rate of decrease in

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*A classification scheme for bank geometry has been developed and is
presented in Chapter 7.

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particle size. This may be largely explained by the reduction in velocity as gradient decreases with an increase in maturity.

The general nature of streams indicates that a stream large enough to require the swimming of a vehicle will be in alluvium. The bank materials will be alluvial and composed of clayey silt or very fine sand to clay. In both the tropics and in temperate areas, larger quantities of non-lateritic gravel are found in terraces and alluvial fans (see Chapter 4), and in river bars. Old terrace deposits in the tropics often contain rotted gravels, usually overlain by a layer of silt.

In a slow sluggish tropical stream, the bottom silt has a greater depth and the banks have a lower height than streams of high velocity (depending upon erosion characteristics of the predominant soil at a given crossing site). This is because the depth of soil to bedrock is relatively greater in such regions, affecting the runoff, the stream velocity, and the lateral stream cross section.

Bank heights are primarily a function of the fluctuations of water depth in an aggradational stream. For cohesive materials, in general, the higher the bank, the greater the slope. Cut banks may be expected to display a slope related to their cohesiveness; slip-off banks (shoals) normally are much more gentle than cut banks, because materials are coarser and thus less cohesive.

When vulnerable materials are scoured from a bank, they can slide down toward the bottom of the channel and be transported along with material eroded from the river bed. Deposited farther downstream, they can influence not only the shape of the channel but also the character of banks.

An analytical discussion of the strength of river banks is presented in Chapter 5.

Chapter 4
STREAM DEPOSITS AND ALLUVIAL PLAINS

The transport and deposit of sediment in a river system, during which bed material is worn even in size, is of special significance in any study concerned with the characteristics of streams as related to vehicle crossings, since crossing sites may have to be chosen in alluvial areas if the upper courses of the river system present insuperable difficulties (mountainous terrain, boulders in the stream, and other obstacles). In such situations, a knowledge of sediment factors, as they affect the structure and materials of banks, is important.

As we have seen, a stream's loss of energy, through a decrease in velocity or volume, causes it to deposit the sediment or debris it is transporting. Such a situation occurs near the upper courses of a river where it flows from a mountainous region and where a "piedmont alluvial plain" or "fan" may be built. It also occurs along the middle courses of a river, where a "flood plain" may develop, and at the terminal area or mouth of a river, where a "delta" may be built out into a standing water body.

PIEDMONT ALLUVIAL PLAINS

The piedmont alluvial plain, more commonly called the alluvial fan, is formed along the base of a mountain, where emerging streams deploy onto a flat plain. The sudden decrease in gradient, as the mountain stream enters the plain, causes deposition of much of the stream's load. A sloping plain is gradually built up, its surface rising to an apex at the point where the stream issues from the mountains; hence the name "fan." Such fans may be a few feet across, or many miles, and are characteristic of arid regions. The stream may flow only a short distance down the sloping fan before it dwindles and disappears, dropping all its sediment. Dry, steep-walled channels extend part way across the fan; these are used by the ephemeral streams in time of flood. If alluvial fans surround a closed basin, the

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central area may become a shallow lake after rainfall, but will dry up at
other times.

The sediment comprising alluvial fans is coarsest near the apex; the
middle slopes are usually composed of sand and silt; and the lower areas
consist of silt and clay. The distribution of plant growth on alluvial
fans is related mainly to differences in soil salinity. Other significant
factors are frequency of freezing temperatures and the time and place of
downslope cold-air drainage.

FLOOD PLAINS

As a stream erodes its channel, it eventually reaches baselevel, which
forms a limit to further downcutting. Now processes of valley widening
begin to predominate. The stream may swing laterally into its banks on the
outside of curves, undermining them and widening its valley through "lateral
erosion." The water flows fastest and deepest on the outside of a curve,
slowest and shallowest on the inside. Deposition of alluvium (sand, silt,
or mud, generally) takes place on the inside of the curve, while the outside
is eroded. In this way the curves become wider and wider, and the stream
is said to "meander." On the inside of a curve, alluvial deposits may take
the form of low sand or mud bars, separated by shallow curved channels.
This pattern of curved markings on the inside of a stream meander is often
called "meander scrolls." The steep curved bluff which is formed on the
outside of a meander by undercutting is called a "meander scarp."

Meandering is basically an exchange of sediment from an upstream
concave bank to a downstream convex bank. In other words, it is a mode of
sediment transport, in which every phase represents a changing relationship
between three closely related variables: the flow and the hydraulic
properties of the channel, the amount of sand moving along the bed, and the
rate of bank erosion.

As such processes proceed, a broad valley just above baselevel is
eventually developed. The meandering stream will swing across every part
of it, leaving deposits of alluvium while widening its curves. For a given
size of stream, character of stream load, etc., there is a general limit to

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the radius of the meander curves that develop. If the meanders are fully
developed, a line can be drawn along each side of the "meander belt,"
which is thus shown to have a nearly uniform width roughly equivalent to
twice the radius of the largest meanders.[7] When the whole flood plain
becomes wider than the meander belt, the meander belt itself may swing back
and forth as time goes on. Figure 8 (p. 25) is a graphical illustration
of the meander belt.

The development of meanders has several consequences. First, as the
curves widen the stream lengthens. Therefore, the gradient or slope of the
stream decreases. If the stream becomes fully loaded with sediment, some
of the load must be dropped, thus further reducing the slope and, hence,
the energy of the stream. Channels tend to fill up, sand bars develop, and
the stream may overflow its banks, spreading sediment on the flood plain.
Such deposits, if continued long enough, eventually will build up the flood
plain surface to a slope on which the meandering stream will be able to
carry all its sediment. Second, as adjacent meanders get wider and wider,
they approach complete circles, and may cut themselves off. Such a cutoff
gives the stream a new, shorter course at that point. The abandoned curved
channel, its ends closed off with sand bars, becomes an "oxbow" lake of
stagnant water.

When flood waters, laden with sediment, suddenly overtop the channel
banks and spread in shallow depth on the flatter land outside, their
velocity is checked and their transporting power is suddenly reduced. Much
of their sediment is therefore deposited in a layer thickest near the stream
channel and thinning out with increasing distance. This process, repeated
year after year, builds "natural levees," which are highest near the stream
channel and slope gradually away from it into stagnant "backswamp" areas.
These swamps may be considerably lower in elevation than the normal river
level. Near the river, the natural levees are composed of coarse silts and
sandy silts, producing a light, well-drained soil. Along the Mississippi,
the dry natural levees are often several miles wide. In contrast, the
backswamps contain the finest silts and clays, and underlying heavy, wet
soils.

One effect of natural levees is to prevent tributary streams from easily entering the main river. Such tributaries may flow long distances parallel to their master stream before they can break through the levee and join it.

Along the sides of many flood plains are higher benches or "alluvial terraces," remnants of a higher flood-plain level. Some broad river valleys have three or even four levels, which may occur in pairs on both sides of the valley. Their surfaces are composed of weak alluvium rather than resistant rock strate.

Variations in vegetation cover on the flood plain will check the overflow in different ways, resulting in variations of alluviation. The type and distribution of vegetation in turn depends upon the frequency and severity of overflow.

DELTA PLAINS

The "delta" is merely the flood plain extended into the body of standing water into which the stream discharges. In most cases the transition from flood plain to delta is arbitrarily placed at the point where "distributaries" begin to diverge from the main stream. In the lower Nile River plain, Cairo is located just above the first distributaries and is therefore at the beginning of the delta. The Mississippi River delta is very different; it projects far out into the Gulf of Mexico with an irregular branching shape, sometimes called a "crow's foot" form. It is apparent that wave action in the Gulf is feeble and is unable to trim off the projections of the Mississippi delta as fast as they are built forward.

The upper surface of a delta slopes gently out to the level of the standing water body, below which it assumes a steeper slope. Exposures of the alluvial beds below the delta surface show that the bulk of the delta is made of beds dipping toward deep water. These are the "foreset" beds. Above them are the flat-lying "topset" beds. Far out in deep water, the foresets flatten out and grade into horizontal "bottomset" beds, which later may be covered up by the foresets as the delta advances. Bottomsets may be composed of fine clays or silts; foresets are coarser, ranging from silt or

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mud in deltas like the Mississippi to sand in small glacial lakes. Topsets are usually coarser than foresets; they are mainly mud and sand in the Mississippi delta but may be coarse gravel in small deltas.

The surface features of deltas are much the same as those of flood plains -- meanders and oxbow lakes, natural levees, and backswamps -- with the addition of distributary channels. Near the sea coast, the branching distributaries extend forward as accretions of sediment build up the delta surface to sea level. Each of the major branches extends seaward between narrow strips of land.

Lateral extension of delta deposits may enclose shallow parts of the sea to form delta lakes, such as Lake Pontchartrain in Louisiana. Another example is the Zuyder Zee, a coastal delta lake in the Netherlands which was formerly an arm of the North Sea.

Chapter 5

ANALYTICAL APPROACHES TO THE STUDY
OF STREAM CHARACTERISTICS

In attempting any quantification of the relationships between the environment and the character of waterways, certain limitations should be considered.

The statement of the problem should require that the waterway be large enough to enable a vehicle to float fully. In turn, streams having average depths of less than 2-3 feet, although quite important in a mobility sense, are more correctly treated as terrain obstacles, hence are not discussed here. In such a very general conceptual approach, streams having depths greater than 2-3 feet will be flowing on bottom deposits in alluvial plains, where they are not completely dependent on the underlying bedrock (its erodability, fault lines, geometry, etc.) for development of their characteristics. Stream-bed materials are relatively homogeneous in comparison with the various geologic formations underlying the stream course.

In mountainous regions, rock structures are complex and variable, and it is difficult to derive simple relationships between prevailing environmental conditions and stream type. The most useful form of relationship is one which involves the fewest environmental parameters and, moreover, involves only those parameters for which data are more-or-less readily available or could be measured without extensive field programs. The most general forms of the desired relationships can be outlined, and the hazards of possible oversimplification accepted. Since there has been so little effort to relate climatology and hydrology, mathematically, analytical treatment may do little more than direct subsequent studies toward this end. However, the accuracy of a predictive scheme has been checked in one instance and was shown to be in fair agreement with the order of the observed value.

Some studies have accepted the assumption that any equations used with the limitations cited above would also hold true for much smaller stream networks (gullies and small intermittent streams). Analysis of distribution by size classes of the latter types of streams would seem to follow empirical relationships outlined for waterways in alluvial plains.

COMPUTATION OF RUNOFF

It is apparent that the absolute quantity fundamental to any stream-character analysis is runoff. Invariably, the portion of precipitation which eventually finds its way into streams and rivers is intricately involved with the amount of water evaporated from free water surfaces and that which is transpired from vegetation. Because of the complexity of computing transpiration, previous methods have been unsatisfactory.[11] The Holdridge system, however, appears to offer the basic framework -- maybe even the explicit relationship -- between climatic factors and evapotranspiration. It is only because the vegetational component of his Life Zones System is directly related to the climatic boundaries that quantitative climatic parameters can be functionally substituted for the hitherto irreconcilable vegetation influence. When this substitution is made, the computation of runoff can be approached with some confidence, but it should be pointed out that runoff, in the context of this discussion, implies a steady-state condition for the ground-water regime.

Classically, runoff has been defined as merely the precipitation which flows over the surface and terminates in a stream, leaving percolation into the soil to be computed by other means. In the present context, the water which percolates into the soil and does not get used by plants (transpiration) is considered to contribute to the ground water supply, forcing a comparable quantity of water to manifest itself eventually in the stream. This is why effective runoff can be considered to be simply the difference between precipitation and evapotranspiration.

By this definition,

$$R_o = P - 0.59\, T_{bio} \left[92 - 45.5 \left(\frac{58.9\, T_{bio}}{P} - 0.34 \right)^{0.534} \right] \qquad (1)$$

where

$$R_o = \text{runoff , } mm^3/mm^2/\text{year}$$

$$P = \text{precipitation , } mm/\text{year}$$

$$T_{bio} = \text{mean biotemperature , } = \frac{1}{12} \sum_{m=1}^{12} T_m$$

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T_m = mean monthly temperature (degrees centigrade) where all temperatures less than 0° are set equal to $0^{\circ}C$

$$R_o' = R_o \cdot M \cdot (0.174) \text{ , mean maximum (wet season) runoff, } ft^3/min/sq \text{ mile} \quad (2)$$

where $\quad M = e^{\left(\frac{10.2\,T_{bio}}{P} + 0.372\right)}$ = rainfall concentration factor for the wet season for normal yearly rainfall distributions, % $\quad (3)$

and $\quad 0.174$ = dimensional conversion constant

Mean maximum (wet season) runoff , R_o' , is also used in two of the analyses which follow, because it is during the wet season that the greatest energy is expended in altering (or forming) channel geometry. By comparison, dry-season flows usually produce but small changes in channel shape.

The factor M is the ratio of 12 (the number of months/year) to the number of wet-season months. Since the number of wet-season months is a function of the potential evapotranspiration ratio, it may be expressed in terms of precipitation , P , and biotemperature, T_{bio} , as in Eq. (3). Abnormal precipitation distributions, however (specifically monsoonal ones), should be treated independently, using the basic relation M rather than its functional relation as expressed by Eq. (3).

If the stream under consideration is so large as to drain basins cutting across widely varying climate types , R_o' must be computed from the sum of the individual climate-areas. The distribution of rainfall within each climate type can also be accounted for with the assistance of adequate climatological data to improve further the resolution of the estimate. However, consistency must be maintained in the degree of refinement of factors contributing to runoff, with all defined and implied factors brought along together.

INTERRELATIONSHIP OF DEPTH, WIDTH, VELOCITY, AND DRAINAGE AREA

The precepts governing the general relationships between stream width, depth, and velocity have been well studied. A few men, like Leopold, Strahler, and Hack, have devoted much of their time to the problem of generalizing the nature of streams. The analyses, until recently, have

been largely of the nature of compilations of detailed observations, in which the climatic parameters were frequently neglected or unrecorded.

Some excellent work by J. T. Hack[12] produced the data necessary to determine approximate quantitative relationships among stream depth, width, velocity, and drainage area, even though his data were not intended for such use. Accepting a very nominal amount of scatter, his data indicate that

$$\frac{u}{w} = 0.24 \left(\frac{AR_o'}{95.3}\right)^{-0.355} \tag{4}$$

where w = the measured width of the stream channel, taken on a plane coincident with the alluvium, ft

u = the average channel depth determined by dividing the crossing sectional area of the stream by its width, ft

R_o' = the mean maximum (wet season) runoff from Eq. (2), ft^3/min/sq mile

A = the drainage area for the stream basin, measured from a topographic map, sq miles

His data also indicate that the corresponding stream width may be computed by

$$w = 8 \left(\frac{AR_o'}{95.3}\right)^{0.491} \tag{5}$$

Both of the above equations have been generalized by taking into account the precipitation and biotemperature averaged for three stations within the study area, and computing the runoff. By combining Eqs. (4) and (5), the average channel depth may be computed by

$$u = 1.073w^{0.28} \tag{6}$$

If a single stream carries the average volume flow of water as indicated by R_o, AR_o must equal the product $w \cdot u \cdot v$, where v = average stream velocity.

Thus,

$$v = \frac{AR_o'}{wu}, \text{ ft/min} = \frac{0.174M \, AR_o}{wu} \tag{7}$$

Substituting Eqs. (5) and (6) into Eq. (7), v may be expressed in terms of mean maximum runoff and drainage area:

$$v' = 1.135 \, (R_o' A)^{0.372} \tag{8}$$

where
$$v' = \text{the mean maximum (wet season) velocity, ft/min}$$

With a slight amount of juggling it is possible to compute the mean dry-season velocity (or stream width and depth) by spreading the residual runoff through the dry-season months.

SIZE DISTRIBUTION OF STREAMS

With the foregoing analyses and one further assumption, it is possible to state the hypothetical relationship between the number of streams in a particular climatic region and their size. If it is assumed that the total runoff in an area is handled by one stream, the geometric division of that flow will permit computation of the size of streams required to keep a constant flow volume. In other words, it is assumed that the major stream in a drainage basin divides into two smaller streams, and that each smaller stream divides into two yet smaller ones, and so on. Thus stated, Eq. (5) can be used to compute the number of streams (N_S) of a given width (w) -- or, conversely, the width of steams of a given number required to maintain a constant flow volume.

$$N_s = 0.722 \, \frac{AR_o'}{(w_N)^{2.04}} \tag{9}$$

The N_S thus computed is equivalent to the classical frequency term, in number of water courses per square mile. This term indicates the number of

streams of a given size which must be traversed for each mile of cross-country travel.

Equation (9) was checked against observations made in Panama[13] during exercise Swamp Fox II. The agreement between computed and observed N_s is generally good. In the Swamp Fox II study area of Panama, the following environmental parameters can be listed (observed $N_s = 4$ streams per mile of traverse):

$$P = 2000 \text{ mm}$$

$$T_{bio} = 26.5^{\circ}C$$

$$R_o = 1915 \text{ ft}^3/\text{min/sq mile}$$

$$M = 1.66$$

$$R_o{}' = 3180 \text{ cfm/sq mile}$$

Let $A = 1$ sq mile and assume effective nominal stream channel widths of $w = 20$ feet.

From Eq. (9) , $N_s = 5.1$ streams per square mile.

It is implicit in the foregoing analysis that the presence of a large stream within an area does not materially alter the number of smaller streams contained therein. A further implication is that the tertiary streams are the sole collectors of runoff, the water collected directly by major streams being negligible. An examination of a number of aerial photographs and stream network sketches, especially in Lueder,[14] indicates that this superposition hypothesis is a reasonable one. However, it remains to be validated quantitatively.

FLUCTUATIONS IN DISCHARGE

In recognition of the fact that streams are an important element in shaping landscape assemblages, some recent investigations in geomorphology

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have concentrated on studying the properties of stream channels and their networks. Some of these studies have dealt with the behavior of a stream's width, depth, and velocity with fluctuations in discharge. In these investigations, it has been found that the adjustment of the dependent variables with changes in discharge at a particular station can be expressed by the following simple exponential equations:

$$w = aQ^b, \quad d = cQ^f, \quad \text{and} \quad v = kQ^m \tag{10}$$

where Q represents discharge, and the variables w, d, and v represent a river's surface width, mean depth, and mean velocity, respectively. The coefficients a, c, and k, and the exponents b, f, and m are derived empirically and are functions of the units of measure. These equations assumed that the mathematical expressions derived empirically with data from moderate and large discharges accurately describe the behavior of the stream for small discharges. That is, the adjustment of the dependent variables to changes of discharge was assumed to remain constant for all river flows less than or equal to bankfull conditions.

But hints of uneasiness concerning these equations appear in the literature. Leopold and Maddock[15] found that widths and depths of streams, for given discharge values, vary widely from one channel section to another, with the result that the coefficients a, c, and k must vary from station to station. In the study of Brandywine Creek,[16] data were collected that appear to indicate that at discharges approaching the bankfull condition, the depth-discharge and velocity-discharge relations differ from those at lower discharges. In this study, the data were not sufficient to indicate a change in the adjustment of the river's behavior. Data collected in three individual studies, dealing with streams in completely different environments, further indicated that the assumption that the values remain constant for all discharges less than bankfull is suspect. Fahnestock[17] states that the extreme values of width and velocity cannot be entirely explained by errors introduced through extrapolation. From data compiled on the White River, he believes that the extreme values suggest instead that the channel is unaffected by the low discharges. Data obtained for the Rio Sana Muerto[18] substantiate Fahnestock's belief and illustrate how

for some streams the width, depth, and velocity do adjust to small discharges.

Figure 9 illustrates the changes that take place for the variables of width, depth, and velocity as discharge varies on the Rio Sana Muerto. Although this is a small river, it illustrates the relationships that may be found at one particular station, as follows:

$$w = 9.7 \, Q^{.34} \, , \quad d = 0.33 \, Q^{.23} \, , \quad \text{and} \quad v = 0.31 \, Q^{.40}$$

The adjustments of the hydraulic variables to discharge take the following form: velocity increases with discharge faster than width, while width increases faster than depth ($m > b > f$). This adjustment of the hydraulic variables to discharge is of a form that is generally different from their adjustment in other studies. The adjustments in the other studies usually take the form $m > f > b$. The explanation for this different adjustment of the channel's hydraulic variables to discharge can be accounted for by an investigation of the shape of the Sana Muerto channel and the movement of water within the channel.

Figure 10 is a cross-sectional diagram of the Sana Muerto channel. It is seen that the channel is slightly entrenched, that the river bed is situated between two nearly vertical river banks, and that the stream bed, while almost level, slopes toward the right bank. Whenever a slight change in the discharge occurs, this configuration causes the right edge of the river to remain practically stationary while the left edge fluctuates. For the range of data collected, a mean depth range of almost 0.1 foot causes the Sana Muerto's width to fluctuate 2.7 feet. By extrapolation, an increase of less than 0.1 foot over the highest recorded field depth (0.35 foot) causes the width of the wetted surface to increase by approximately 4 feet. At this point, the river completely covers the whole river bed. Any further increase in the water depth will cause very small increases in width, until flood stage, since the river banks are almost vertical. The moment that the water in the channel touches both banks at the same time, a completely new relation among the simultaneous changes of width, depth, and velocity to discharge must occur. With the Sana Muerto occupying the whole stream bed, the width of the wetted surface can no longer increase at the
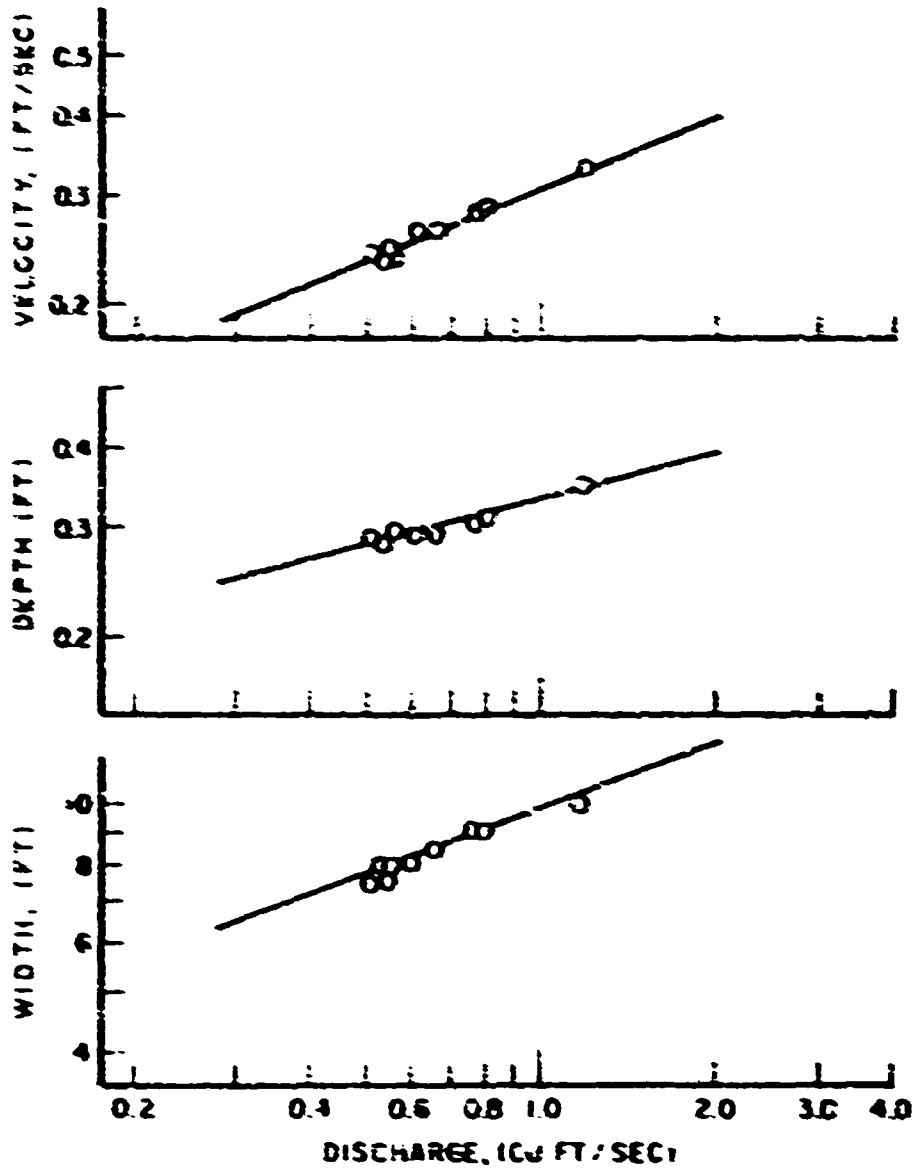
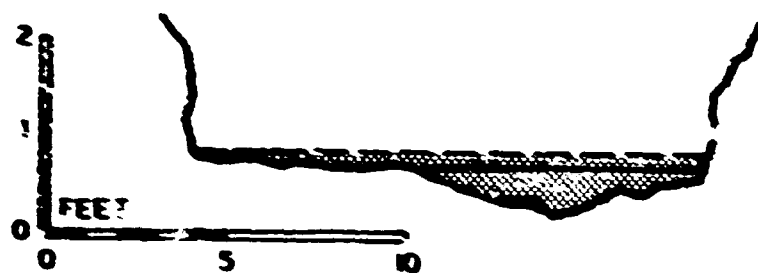FIGURE 9. VALUES OF VELOCITY, DEPTH, AND WIDTH AT VARIOUS DISCHARGE RATES, ON THE RIO SAN. PUERTO[20]

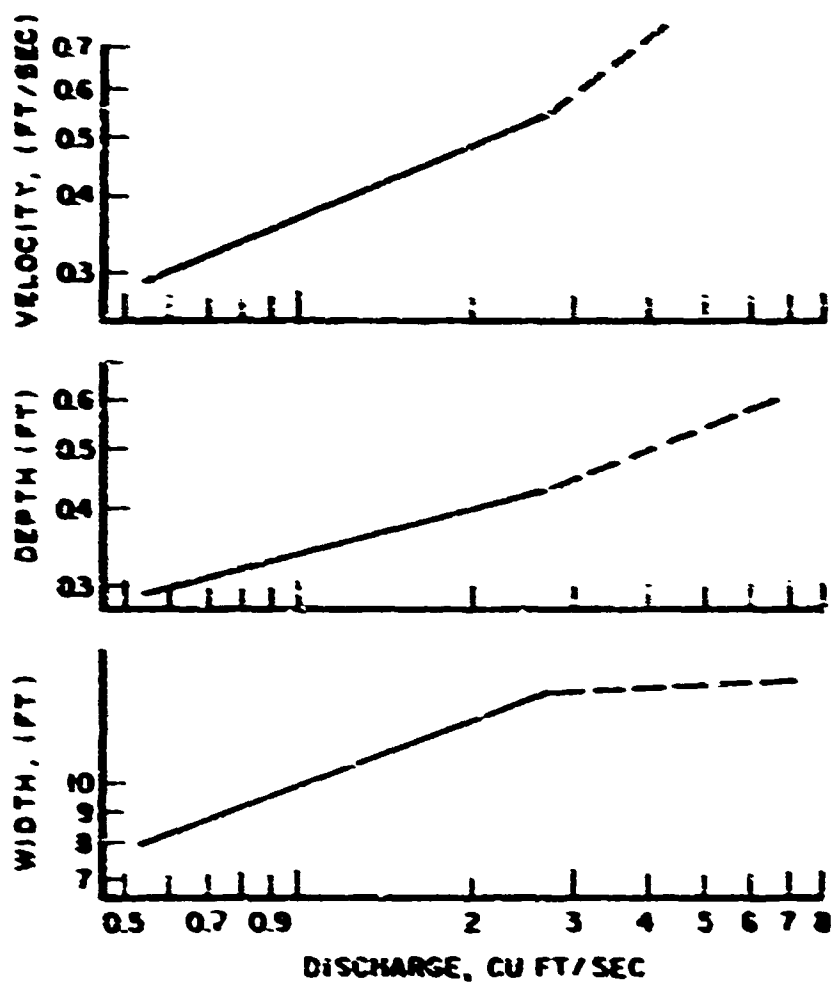FIGURE 18. PROFILE OF THE SAUR REED CHANNEL [18]

DISCHARGE, CU FT/SEC

FIGURE 11. REGRESSION PLOTS OF FIELD DATA TAKEN AT SAUR MUERTO STATION [18] (DOTTED LINE IS FOR BED-FULL CONDITION)

same rate as during the smaller discharges. Consequently, the equations describing the adjustment of the hydraulic variables at the low discharges will not be valid once the stream impinges on both banks. With the water surface covering the whole stream bed, the rates of velocity and depth will probably increase as the width rate must decrease (Fig. 11). It therefore appears that numerous extrapolations of the hydraulic variables to low discharges, which are based on curve-fitting equations derived from data of moderate and high discharges, most likely are invalid. Since it is impossible to predict how the decrease in the rate of change for the width will be absorbed by changes in the rates of change for the velocity and depth, the new values for b , f , and m are undefined. But as the channel will become more rectangular with increases in the height of the water surface, it is reasonable to assume that the exponents would take the common form of m > f > b ; It must be emphasized that this presumption is made by assuming that once bedfull conditions are attained, the hydraulic variables will continue to adjust to discharge in the identical form. This assumption is justified by the fact that all previous results indicate that the variables' adjustment to discharge is exponential when river beds are completely covered by the stream.

STRENGTH OF STREAM BANKS

It has been noted that in a stream large enough to require swimming of a vehicle, bank materials will be alluvial, ranging from very fine sand to clay. Cut banks usually contain the finer soils along the stream and slip-off banks often consist of an admixture of (1) the coarser fraction of the alluvium and (2) bed material which is transported by the stream at high water.

Generally, then, cut banks will be slightly cohesive on the surface. The subsurface soil cohesion (c_p) is approximately equal to the surface soil cohesion (c_u), possibly < 3-4 psi ; the angle of internal soil friction in the subsurface (φ_p) is approximately equal to the angle of internal soil friction on the surface (φ_u) and should range between 20 and 30 deg. Shoals are normally composed of purely frictional soils (i.e., $c_p = c_u = 0$; $\varphi_p = \varphi_u = 30$ to $35°$) near the water line, and grade into alluvial

character at the top of the bank. Subsurface cohesion may be quite high
in high banks, but proximity to water will reduce surface cohesion.
Therefore, the higher the bank, the greater its soil strength and the more
critical the surface soil properties become.

By breaking a stream cross-sectional profile into segments, some rough
quantification can be made, considering two positions along the course of
the stream (see Fig. 12). The listed soil-strength values, taken from
Cohron,[13] were based not on measurements, but on the author's experience.
The values, however, seem to be consistent with the observations of others.

Case 1. <u>Mean water level significantly below the top of the bank (upstream)</u>.

A. Alluvial material

Bank surface-layer properties:

Subsurface soil cohesion (c_p) is high; surface soil cohesion
(c_u) is low; angle of internal soil friction in the sub-
surface (φ_p) and surface (φ_u) are typical of consolidated
medium-grain-sized soil. Critical layer's soil strength
(RCI) is high enough to provide support for the better
(lower ground pressure) vehicles.[*]

For the surface,

$$c_p = c_u \approx 3\text{-}4 \text{ psi}$$

$$\varphi_p = \varphi_u = 20^\circ \sim 30^\circ$$

$$RCI > 80 \text{ near the surface}$$

Smooth, relatively firm.

_____

[*]For cone index (CI), vehicle cone index (VCI), and remolded cone index
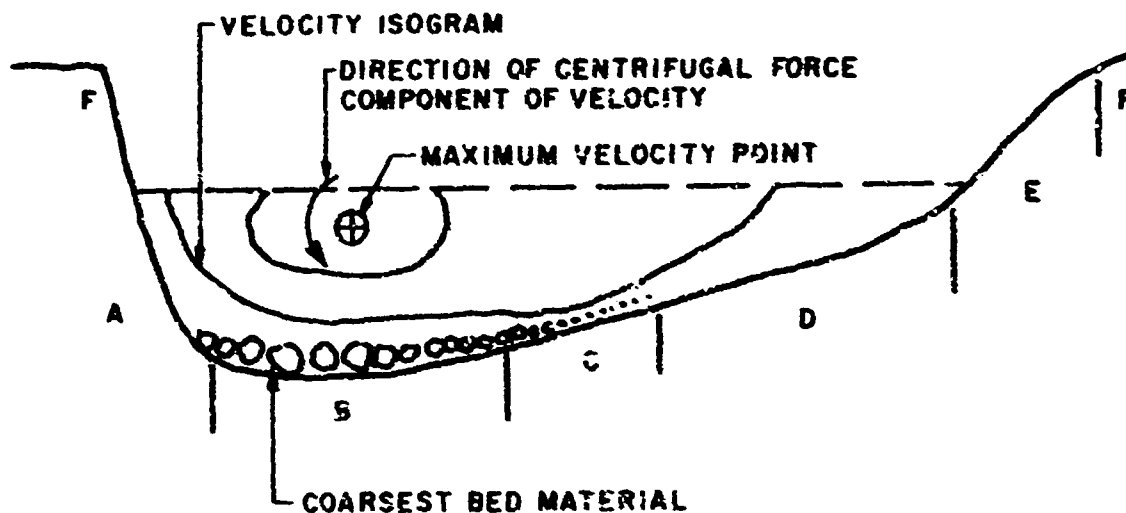(RCI), see Ref. 19.

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FIGURE 12. TYPICAL RIVER CROSS SECTION
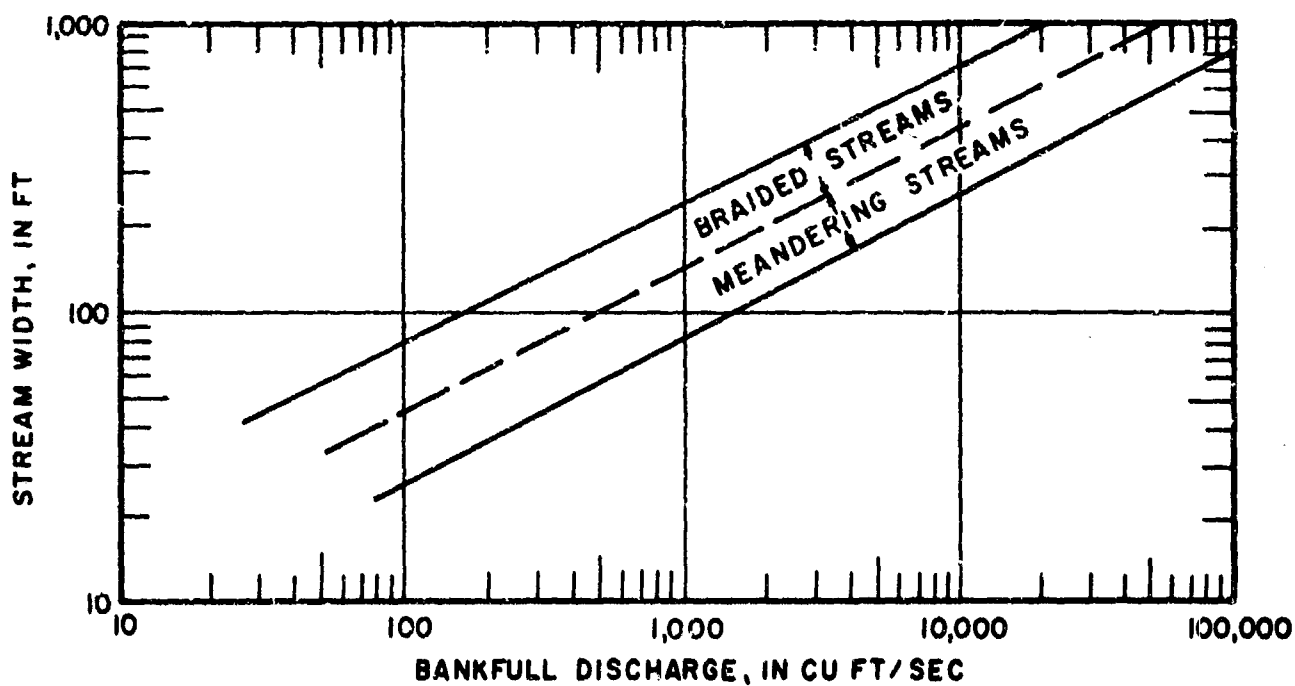
FIGURE 13. GENERAL RELATIONSHIPS BETWEEN STREAM WIDTH AND BANKFULL DISCHARGE

B. Bed material

This is coarse by comparison, ranging from 1/2" diameter
gravel to boulders possibly up to 12" in diameter,
transported from far upstream at peak (long-term) flows.
Size is related to dip slope, fracture, cleavage, and
other physical properties of the outcrop (coarse material).

$$c_p = c_u = 0$$

$$\varphi_p = \varphi_u \cong 30^o$$

$$RCI > 300$$

Purely frictional; rough; firm.

C. Bed-shoal transition

Coarsest fraction of material transported in suspension
by the stream, mixed with finer fractions of bed
materials.

$$c_p = c_u = 0$$

$$\varphi_p = \varphi_u \cong 30^o$$

$$RCI > 200$$

Purely frictional; slightly rough surface; firm.

D. Submerged shoals

Largely the coarse fraction of adjacent alluvial materials.

$$c_p = c_u = 0$$

$$\varphi_p = \varphi_u \cong 20^o$$

$$RCI > 150$$

Purely frictional; smooth; firm.

E. Exposed shoals

Miu-range size of adjacent alluvial material; clay
particles largely absent. Very slightly cohesive
(negligible for mobility computations because it is
easily destroyed, especially in the presence of
water washed ashore upon egress of vehicle).

$$c_p \cong 8\text{-}10 \text{ psi}$$

$$c_u \cong 0$$

$$\varphi_p \cong \varphi_u \cong 25^\circ$$

$$RCI > 80$$

Smooth; relatively firm.
Maximum slopes of the order of 35-40 percent.

F. Bank materials

Particle size in alluvium decreases directly in
proportion to the distance from the head of the
stream. It is therefore possible to estimate
the approximate texture (i.e., grain size) of
bank materials. This information, together
with soil moisture contents, permits reasonable
prediction of bank strength.

Bank materials are normally several orders finer
than stream-bed materials. However, at this time,
there is no good way to estimate surface shearing
strength of banks except through poorly established

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links between texture, moisture content, and
shearing strength.

Case II. **Mean water level near top of bank (in or near alluvial fans and river deltas)**.

A. **Alluvial material**

Most probably silty clays; moisture content near
saturation level; flooded during the rainy season
in the drainage basin (see below).

Natural levees (often under cultivation) border the
stream on both sides and are composed of fine to
silty sands. Nearly pure silt may be found near
the mouth of the river, becoming coarser upstream.
For the surface,

$$c_p \cong 6\text{-}12 \text{ psi}$$

$$c_u \cong 1\text{-}2 \text{ psi}$$

$$\varphi_p = \varphi_u \cong 20^o - 25^o$$

$$RCI > 180$$

Smooth; firm.

Back swamps are a common feature on river deltas,
associated, in part, with a greater frequency of
flooding along the lower course of the main stream.

Dry

$$c_p \cong 20\text{-}30 \text{ psi (brick-like)}$$

$$c_u \cong 4\text{-}6 \text{ psi}$$

$$\varphi_u \approx \varphi_p \approx 12^\circ - 15^\circ$$

$$RCI > 200$$

Smooth unless very dry and cracked; hard.

Inundated or saturated

$$c_p \cong c_u \cong 2\text{-}3 \text{ psi}$$

$$\varphi_u = \varphi_p \cong 6^\circ - 9^\circ$$

$$RCI \cong 20\text{-}60$$

Smooth; soft.

B. Bed material

Nominally sand; purely frictional; firm; smooth.

$$c_u = c_p = 0$$

$$\varphi_p = \varphi_u \approx 25^\circ$$

$$RCI > 80$$

Smooth; relatively firm.

C. Bed-shoal transition

Nominally fine sand to silty sand.

$$c_p = c_u = 0$$

$$\varphi_p = \varphi_u \approx 20^\circ$$

$$RCI > 40\text{-}80$$

Smooth; relatively soft.

D. Submerged shoal

Nominally silt to clay, mud.

Depth of mud: up to approximately two feet.

Mud strength, 0.

Lower layers of mud, RCI ~ 10-20.

c and φ both low.

Smooth; very soft.

E. Exposed shoal

Small or non-existent.

F. Bank materials

Unimportant, since banks are small or non-existent.

The following table presents Lueder's computations for critical bank height,[14] taken directly from classical soil mechanics. They are estimates at best, but have proven to be useful approximations. The c_e and φ_e used by Lueder correspond to c_p and φ_p for subsurface soil. Lueder uses N_s to mean the bank stability factor; but this should not be here confused with N_s used previously for the number of streams.

THEORETICAL CRITICAL HEIGHTS FOR VARIOUS SOIL TYPES COMPUTED ACCORDING TO THREE FORMULAS

(For $\beta = 90^\circ$ and $\gamma = 120^\circ$)

	Theoretical Critical Heights, ft (reduced from H_c case)		
	H'_c Reduced 4% from H_c case	H''_c Reduced 36% from H_c case	H'''_c Reduced 50% from H_c case
Case I -- Cohesive Frictionless Soils ($\varphi_e = 0$)			
Formulas..........	$H'_c = \frac{c_e}{\gamma} N'_s = \frac{3.85 c_e}{\gamma}$ $= \frac{1.93 q_u}{\gamma}$ (see note 1)	$H''_c = \frac{c_e}{\gamma} N'_s = \frac{2.57 c_e}{\gamma}$ $= \frac{1.29 q_u}{\gamma}$	$H'''_c = \frac{c_e}{\gamma} N''_s = \frac{2.00 c_e}{\gamma}$ $= \frac{1.00 q_u}{\gamma}$
Very soft clays ($q_u = 0.25$)	8	5	-
Soft clays ($q_u = 0.25$-0.5)	8-16	5-11	4-8
Medium clays ($q_u = 0.5$-1.0)	16-32	11-21	8-17
Stiff clays ($q_u = 1.0$-2.0)	32-64	21-43	See note 2
Very stiff clays ($q_u = 2.0$-4.0)	64-128	43-85	See note 2
Extremely stiff clays ($q_u = 4.0$ up)	128 up	85 up	See note 2
Case II -- Soils Having Cohesion and Friction (φ_e and $c_e > 0$)			
Formulas..........	$H'_c = 4.2$ to $7.5 \frac{c_e}{\gamma}$ $= 2.1$ to $3.75 \frac{q_u}{\gamma}$	$H''_c = 2.8$ to $5.0 \frac{c_e}{\gamma}$ $= 1.4$ to $2.5 \frac{q_u}{\gamma}$	$H'''_c = 2.2$ to $4.0 \frac{c_e}{\gamma}$ $= 1.1$ to $2.0 \frac{q_u}{\gamma}$
For values of c_e equal to q_u of 0.25 to 1.0 only:			
$\varphi_e = 5^\circ$	9-36 ($N'_s = 4.2$)	5-21 ($N'_s = 2.8$)	4-16 ($N''_s = 2.2$)
$\varphi_e = 10^\circ$	9-37 ($N'_s = 4.5$)	6-24 ($N'_s = 3.0$)	5-20 ($N''_s = 2.35$)
$\varphi_e = 15^\circ$	10-41 ($N'_s = 5.0$)	6-25 ($N'_s = 3.2$)	5-21 ($N''_s = 2.6$)
$\varphi_e = 25^\circ$	13-50 ($N'_s = 6.0$)	8-32 ($N'_s = 3.9$)	6-24 ($N''_s = 3.1$)
$\varphi_e = 35^\circ$	16-64 ($N'_s = 7.5$)	10-41 ($N'_s = 5.0$)	8-32 ($N''_s = 4.0$)

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Case II, cont'd

For values of c_e equal to q_u of 1.0 to 4.0 only:

$\varphi_e = 5°$	36-144 (N's as above)	21-84 (N''s as above)	16-64 (N'''s as above)
$\varphi_e = 10°$	37-148	24-96	20-80
$\varphi_e = 15°$	41-164	25-100	21-86
$\varphi_e = 25°$	50-200	32-128	24-96
$\varphi_e = 35°$	64-256	4i-164	32-128

Case IIIA -- Semi-cohesionless Soils (c near zero)

Formulas	$H'_c = 7.5\dfrac{c_e}{\gamma} = 3.75\dfrac{q_u}{\gamma}$	$H''_c = 5.0\dfrac{c_e}{\gamma} = \dfrac{2.5q_u}{\gamma}$	$H'''_c = \dfrac{3.9c_e}{\gamma} = \dfrac{1.95q_u}{\gamma}$
For value of $\varphi_e = 35°$ (dense sand) and $q_u = 0.1$ only	6	4	3
			Say 2 to 3 feet because of seepage forces, surface cracks; temporarily greater

Case IIIB -- Cohesionless Soils (c = 0)

NA	0	0	0
			Slightly or temporarily greater because of local surface effects, leaching, etc.

Note 1: Unconfined compressive strength , q_u , is in tons per square foot.

Note 2: It is doubtful that frictionless soils will stand vertically and unsupported for appreciable lengths of time, to the heights indicated by these formulas. Therefore no heights are included.

Chapter 6

INDIRECT METHODS FOR OBTAINING QUANTITATIVE STREAM DATA

PROPOSED SYSTEMS OF APPROACH

Leighty[20] describes a system which uses indirect methods for obtaining quantitative data for hydrologic features. It begins with the identification of a feature from an air photo (e.g., a meander) and yields quantitative estimates of bank height, stream width, channel depth, and cross section, based upon previous measurements of analogous structures. Leighty considers these measurements to be at best approximate and often inadequate, because of the small scales used on many aerial photos. (It should be noted that considerable experience is required to interpret air photos for this purpose.)

Leopold[21] has proposed an approach based upon quantitative geomorphology, air photos, and maps. For example, it is possible to begin by making a measurement of stream width from an aerial photo. With this measurement and Fig. 13 (p. 47), an investigator can obtain an estimate of the bankfull discharge to a reasonable degree of accuracy. Having obtained the bankfull discharge, he can then determine the mean velocity and the mean depth by using Fig. 14. This technique should yield an estimate accurate to ±30 percent for mean velocity and ±50 percent for mean depth.

If a topographic map is available for the area, the margin of error can be reduced by utilizing slope data. With measurements from an air photo and a topographic map, it is possible to use two equations (one utilizing the Manning relationship):

$$Q = wdv \qquad (11)$$

and
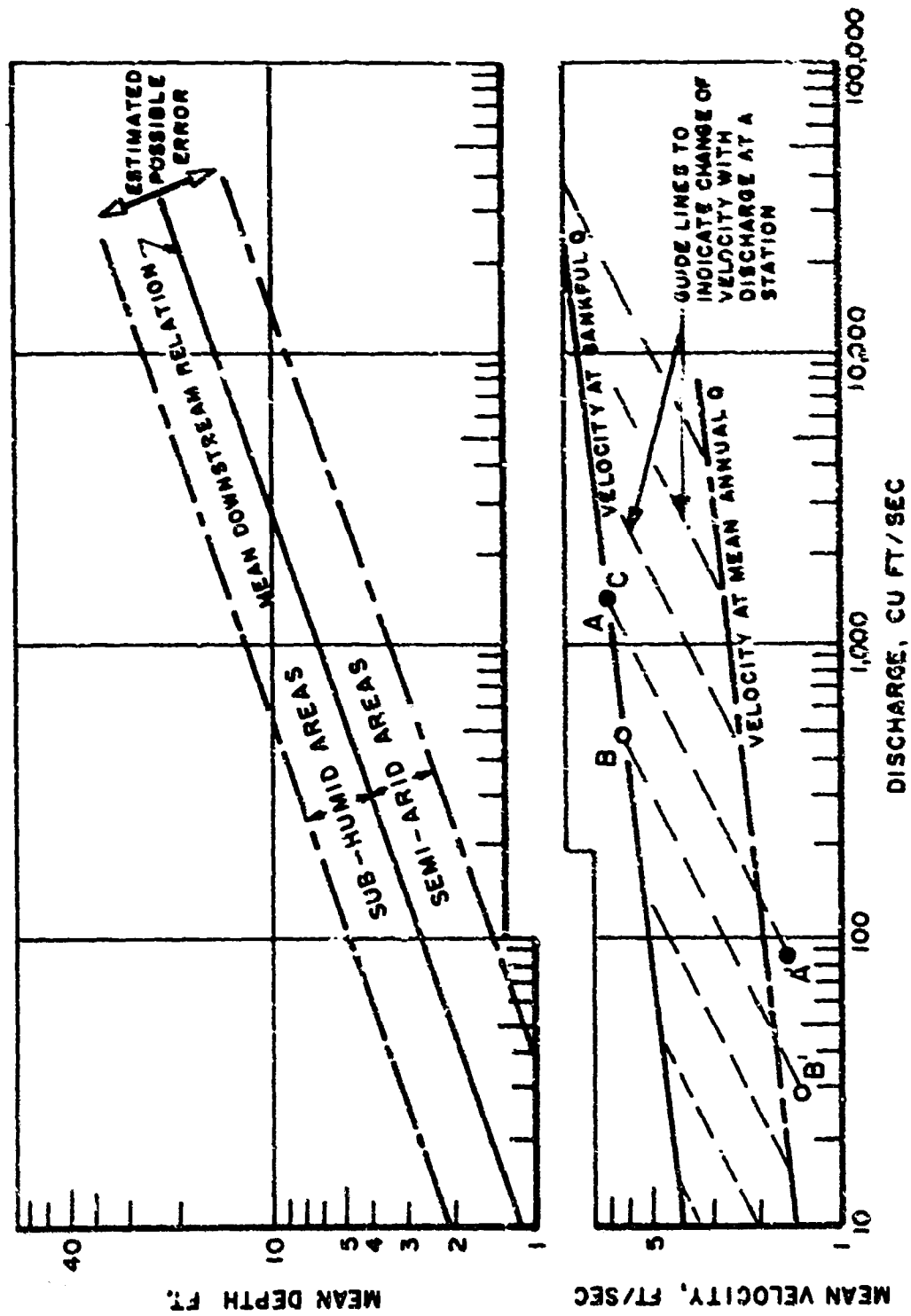
$$v = 1.486 \frac{R^{2/3} S^{1/2}}{n} \qquad (12)$$

FIGURE 14. GENERAL RELATIONSHIPS BETWEEN VELOCITY AND DEPTH VS. DISCHARGE

where Q = discharge

           d = depth

           w = width

           v = velocity

           R = hydraulic radius[*]

           S = mean slope

           n = Kutter's coefficient of roughness
                 parameter
                 Examples: Dry excavated earth canals,
                             $n = 0.016$
                             Canals excavated from rock,
                             $n = 0.033 - 0.040$
                             Concrete linings, $0.010 - 0.013$

Depth can then be estimated as a function of discharge, width, and slope.

Leopold[8] believes that if a river basin is generally homogeneous, the flow characteristics in one part should closely approximate the flow elsewhere in the basin. Therefore, measurement of the properties of an accessible tributary can provide adequate data for an inaccessible main stream. No comparison studies have been found which deal with the relative merits of the systems described by Leighty and Leopold. It is recommended that the Leopold method be used in conjunction with field tests, to improve indirect methods.

It has been qualitatively determined that stream-channel geometry takes form largely (almost exclusively) during times of peak flow, when the greatest energy is encountered. During these times, stream banks may be just high enough to contain the flow, but subject to sporadic flooding. If we can assume that R_o' represents the mean maximum (wet season) flow and that it just fills the banks, the depth may be computed.

The nominal water depth during the dry season may be computed from R_o'', the mean minimum (dry season) flow. If we let M'' be the rainfall modulation factor for the dry season and equal to $\frac{1}{M}$ (where M is as

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[*] Cross-sectional area of stream divided by wetted linear surface.

given in Eq. (3)), then a dry-season runoff may be computed as

$$R_o'' = 0.174 R_o M'' \approx 0.174 \frac{R_o}{M} \qquad (13)$$

Since we have assumed that the bank height is nearly zero during mean maximum flow, then at mean minimum flow (R_o''), the bank heights should be at a maximum. The difference between the corresponding depths should indicate the maximum bank height.

If u' = mean wet-season water depth

       u'' = mean dry-season water depth

and if h_b = maximum bank height

then

$$h_b \cong u' - u'' \qquad (14)$$

The validity of Eq. (14) has yet to be determined.

AERIAL PHOTOGRAPHY

Aerial photography has been used as a basic tool in many analytical studies. The general watershed environment (geology, topography, and drainage pattern) is best analyzed from aerial photographs, and investigations are now under way to find a means of determining the distributive and quantitative aspects of soil moisture, evapotranspiration, sedimentation, and snow cover. Preliminary work has been done on the identification of channel characteristics and stream flow (see "Final Report on Alaska Stream and Basin Characteristics Pertinent to Military Mobility," by C. W. Slaughter, with contributions by P. V. Sellman, S. L. Dingman, R. H. Hauger, E. A. Joering, and J. Brown; Cold Regions Research and Engineering Laboratory, Hanover, N. H., July 1968).

The results of the CRREL study are encouraging and suggest that air photo analysis, together with topographic map interpretation, can provide

useful surface-water data (though of a preliminary nature). Aerial photographs have already been proven a reliable source of ground-water information, and it appears that with further development a complete hydrologic analysis may be obtainable through interpretation.

Another study, to determine the practicality of such work, is under way in the Costa Rica area. The object of the study is to assess trafficability cover and concealment, and the influence of an inaccessible area upon a communications system. Studies by ground personnel are being compared with aerial photographs to see if there is a relationship which has value for military purposes. Preliminary results are considered promising, and future studies are planned.

It is apparent that aerial photography could be extremely valuable in the planning of cross-country operations, by determining the speed and direction of stream flow and supplying information relative to the environment surrounding the waterway. Drainage channels, wet or dry, are readily recognizable on infrared photographs, as are certain vegetation, soils, bedrock topography, and climatic conditions. In photographs, the extent of gullying in an area is apparent; and detailed tracings of an entire drainage network can be made. Because certain kinds of gullying are associated with certain soil conditions, pattern analysis can help identify soil type in the immediate area.

Land surfaces composed of fine-grained silts and clays, which are relatively impervious, have many gullies; whereas sands and gravels, being rather permeable, have few or no gullies. In addition to soil, there are other factors which govern gullying, such as climate, vegetation, ground slope, topography, and local land practices. The shapes and gradients of gullies provide the most important clues for diagnosing local soil conditions. A gully exposes the soil profile, sometimes very deeply, and its sides reveal the character of subsurface materials.

PREDICTION OF STREAM FREQUENCY FROM MAPS

A study by the Cold Regions Research and Engineering Laboratory (CRREL) showed that topographic maps are useful for rapid determination of magnitude

and frequency (spacing) of rivers.[22] Rivers with a wetted water width of 20 feet or more are considered significant for military river crossings.[23] The frequency of this class of rivers was found to be shown best on maps with a 1:1,000,000 scale; smaller rivers can be determined from 1:250,000 maps. It was also found, however, that "channels or streams less than 3 feet in depth cannot be accurately determined without additional projections from the most detailed map scales." The relationship between river frequency and map scale is shown in Fig. 15.

Stream frequency may be determined by drawing random transects on a map and counting the number of intersections with "blue line" streams on the map. The CRREL study also included an analysis to establish the number of transects required to generate any specified desired degree of accuracy. For example, a 95-percent probability that the measured mean stream frequency would be within 0.002 streams/mile would require the averaging of the results of 60 randomly drawn transects when using a 1:1,000,000 scale map. The stream frequency in some areas of military interest is 0.1 streams/mile (i.e., one stream every 10 miles).

Another method of estimating stream frequency from maps uses the following empirical relationship of frequency to drainage density:

$$N = 0.637 \, D_D \tag{15}$$

where

N = stream frequency (spacing), streams/mile

D_D = drainage density (ratio of total length of streams to drainage basin area), miles/miles^2

To employ Eq. (15), the total "blue line" channel length is measured with a map wheel, and the areas must cover the entire drainage basin. A plot of a number of computed data points, compared with the theoretical line of Eq. (15), is shown in Fig. 16.

The relationship between stream frequency, as determined by this method, and map scale shows the same general trend (i.e., increasing frequency with decreasing scale ratios) as that determined by random transects. Thus, the 1:1,000,000 map scale is best when determining river frequencies which are significant for military river crossings (i.e., a wetted water width greater than 20 ft).
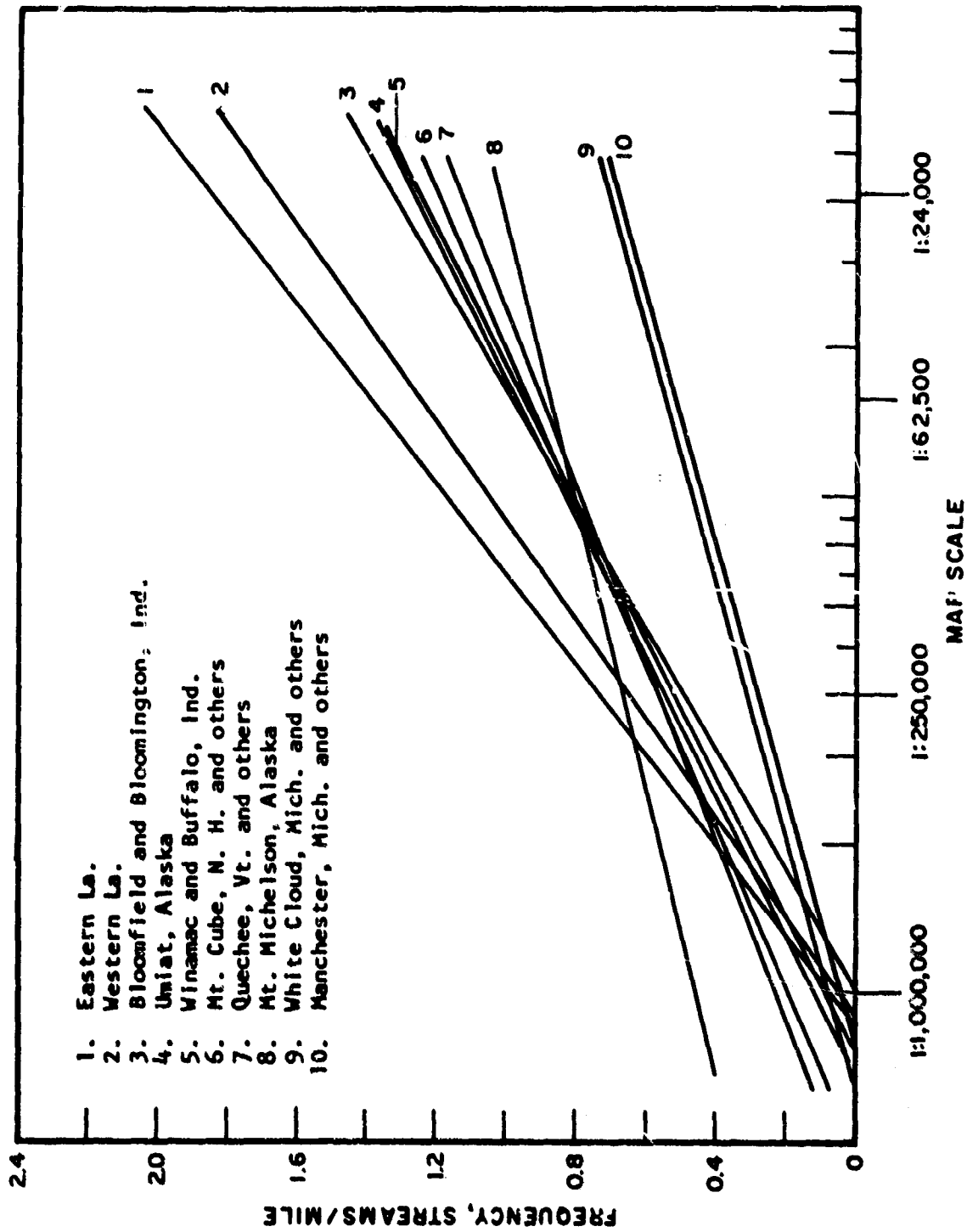
60

FIGURE 15. A SUMMARY PLOT OF THE REGRESSION LINES OF STREAM FREQUENCY VS. MAP SCALE DATA[23]

1. Eastern La.
2. Western La.
3. Bloomfield and Bloomington, Ind.
4. Uniat, Alaska
5. Winamac and Buffalo, Ind.
6. Mt. Cube, N. H. and others
7. Quechee, Vt. and others
8. Mt. Michelson, Alaska
9. White Cloud, Mich. and others
10. Manchester, Mich. and others
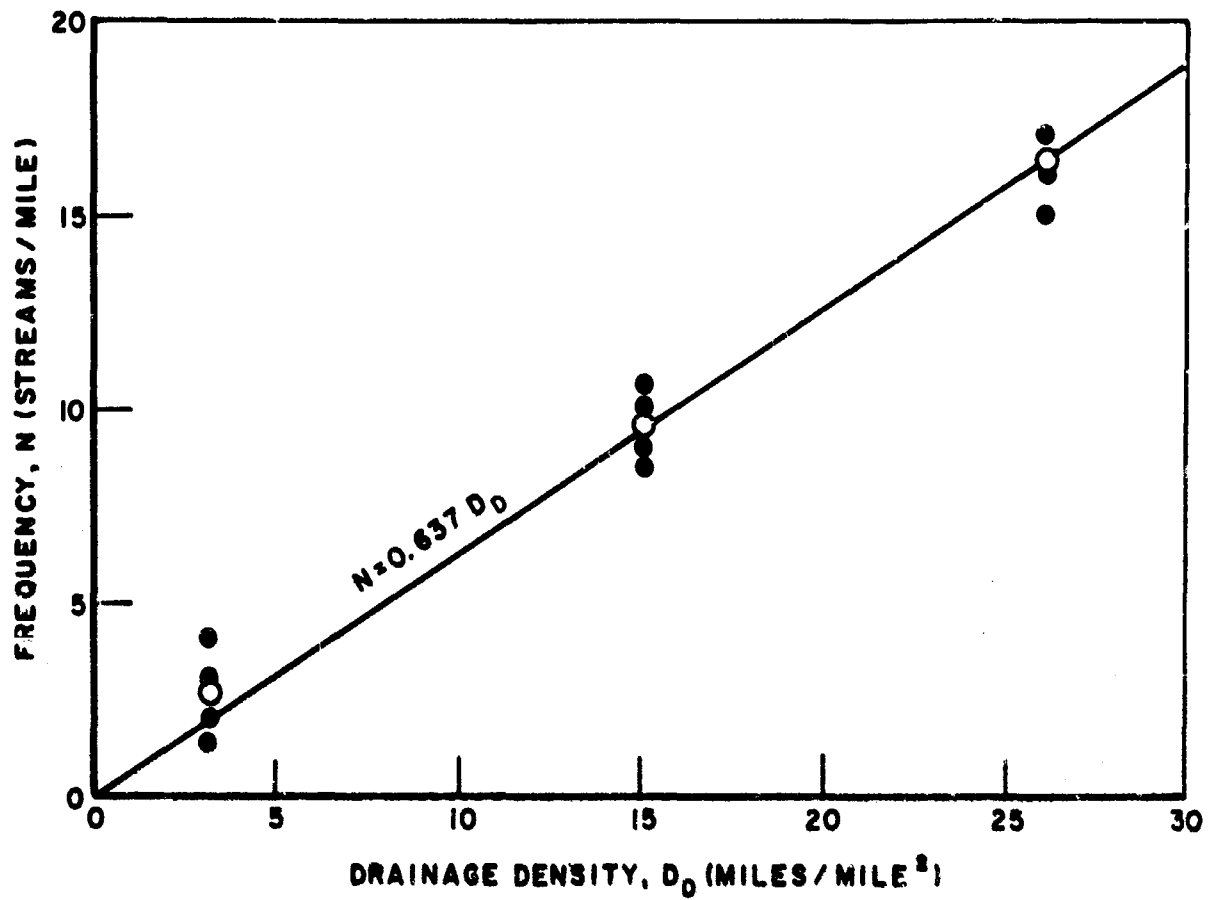
FREQUENCY, STREAMS/MILE

MAP SCALE

FIGURE 16. COMPARISON OF FIELD DATA WITH
EMPIRICAL FORMULA (EQUATION 15)

The method is obviously very time-consuming. However, drainage density is a basic geomorphologic parameter and is frequently available from published literature. In most drainage-basin studies, though, geomorphologists extend the channels to include depressions other than blue-line channels. The frequency determined from published drainage-density data will, therefore, be higher than that which would be measured by a field survey of rivers of military significance.

Chapter 7

FACTORS AFFECTING ENTRANCE AND EGRESS FROM STREAMS

BANK GEOMETRY

For many years, researchers have been studying the problem of river crossing by examining the performance of vehicles in water. If the vehicle could float and proceed at a reasonable speed, it was considered capable of a river crossing. By hindsight, this assumption was obviously false, for the most difficult part of any river crossing is exiting from an unprepared bank. Thus the single, most important parameter with regard to a river crossing is the geometric form of the banks.[24]

The significance of the bank slope was further indicated by tests of the M-113 exiting capability, conducted by Aberdeen Proving Ground. These tests demonstrated a maximum slope-climbing ability of only 17 degrees (30 percent) for attempts to exit from water.[25] Unpublished test reports by the Land Locomotion Division, on exiting tests conducted with the M-113 in Alaska, Panama, and Michigan, tend to confirm these results. A survey of rivers in the United States that found bank slopes greater than 25 degrees (47 percent) on 62 percent of the rivers encountered,[26] and a similar survey in Thailand that found bank slopes greater than 30 degrees (58 percent) on 76 percent of the rivers measured,[27] further underscored the importance of the bank.

Prior to 1967 there was little "hard" data available on river-bank geometry.[28] Since then, however, a few field surveys have been conducted,[26,27,29,30] from which an empirical relationship has been developed to express the severest of all banks by an equivalent vertical step height[23,24] (Fig. 17). This estimated value has been called the "geometric severity factor" (GSF).

$$GSF = H \sin^2 \beta \qquad (16)$$

where
$$H = \text{bank height}$$
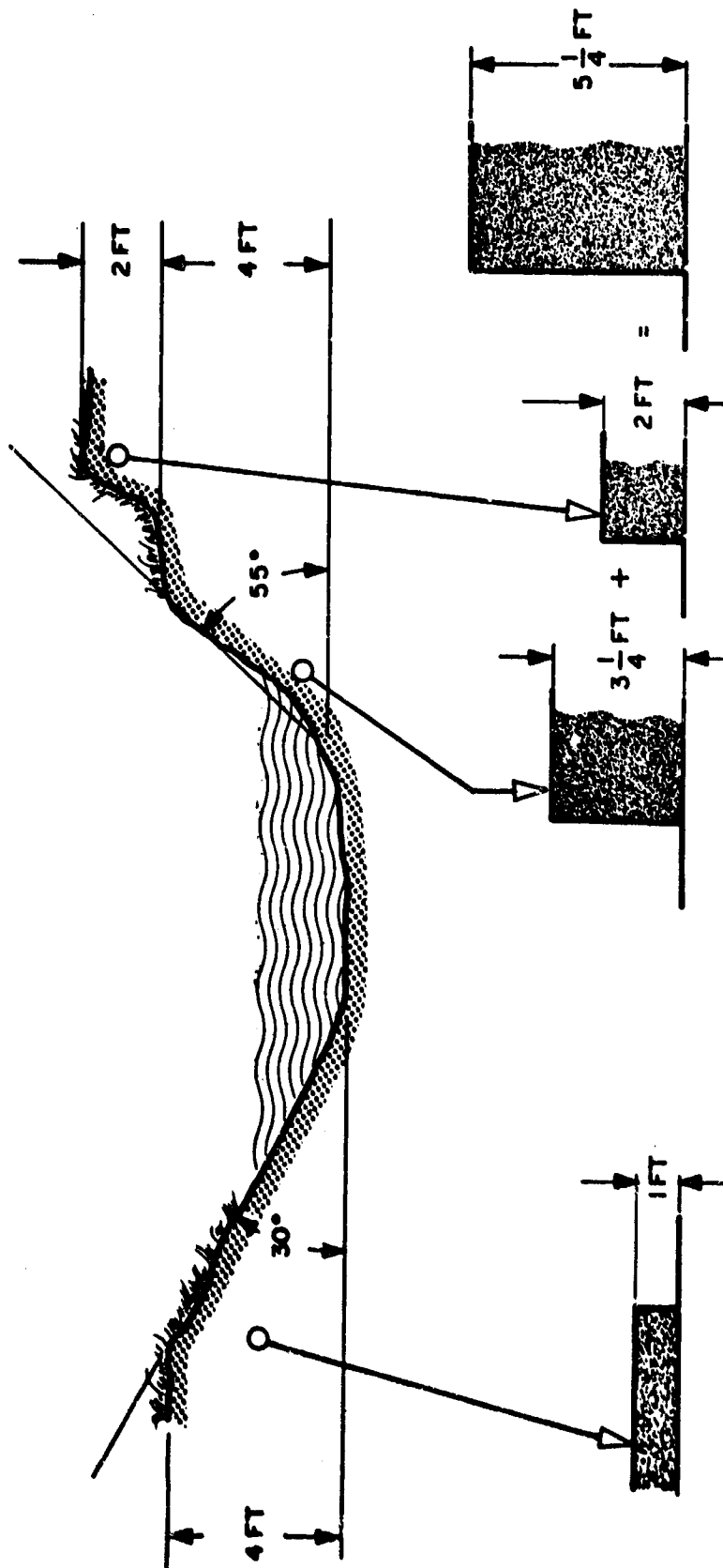$$\beta = \text{bank slope angle from the horizontal}$$

FIGURE 17. TYPICAL RIVER CROSS SECTION WITH APPROPRIATE EQUIVALENT VERTICAL STEP HEIGHTS FOR VARIOUS BANKS, AS COMPUTED FROM EQUATION 16

Vehicle exiting performance is estimated by determining the vehicle's vertical step-climbing ability on both non-deformable (wood, concrete, etc.) and deformable (sand, clay, etc.) steps. The vehicle is then predicted to have a GO capability on any bank whose GSF is less than the non-deformable step-climbing ability of the vehicle; the vehicle has a MARGINAL capability of negotiating a bank with a GSF which is less than the deformable step-climbing ability of the vehicle; and it has a NO-GO capability for any bank with GSF above the deformable step-climbing ability of the vehicle (Fig. 18).

Frequency distributions of geometric severity factors for the Eastern United States and Thailand, developed from the survey data in References 26 and 27 are given in Table 1. Tests indicate that the M-113 armored personnel carrier has a GO capability of 2 ft and a MARGINAL capability of between 2 and 4 ft. Using Table 1, Table 2 presents an evaluation of its exiting capability.

The unpublished results of field tests conducted with an M-113 to establish the validity of the GSF indicate the method to be useful as a gross estimate of the impediment to exiting that the geometry of a particular bank represents. It was evident that the riverine environment is very severe with respect to the M-113's exiting capability, and that any negatively biased scheme (i.e., one that tends to predict NO-GO) will enjoy success.

Several computer programs[31,32] and one type of scale-model test[33] have been developed to predict vehicle exiting performance on a uniform slope. The results of this work show that bank geometry is important even if the bank is a uniform slope, because --

(a) The resisting force developed by the gravity component, parallel to the slope, is a major factor impeding vehicle exit.

(b) A "bridging" effect between the buoyant portion of the vehicle and the part of the suspension system which is in contact with the bank produces nominal ground pressures as much as twice that developed on level ground. When this occurs, immobilization usually results.

The computer simulations were also used in a parametric analysis (Part II of this study), with some additional study of compound bank angles, steps, and soil-strength parameters in the simulation. A comprehensive exiting model may be developed in the next few years.
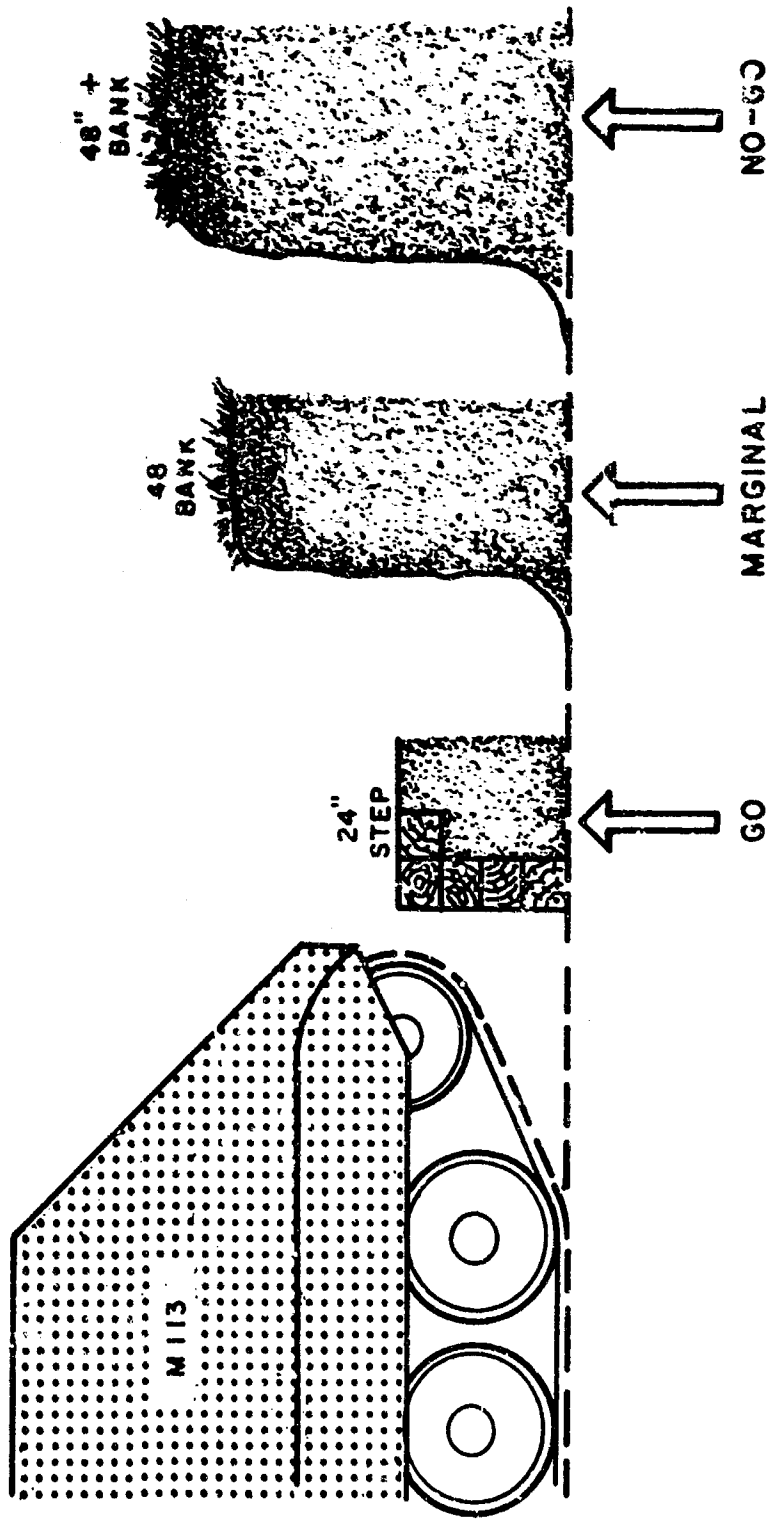
FIGURE 18. STEP OBSTACLES FOR EVALUATING THE GEOMETRIC SEVERITY FACTOR (GSF); HEIGHTS SHOWN ARE FOR THE M113 ARMORED PERSONNEL CARRIER.

Table 1.

FREQUENCY DISTRIBUTIONS OF BANK GEOMETRIC SEVERITY FACTORS[26,27]

GSF (ft)	Eastern United States			Thailand		
	No. of Banks	Percent of Total	Cumulative Percent	No. of Banks	Percent of Total	Cumulative Percent
1	29	12.9	12.9	10	8.1	8.1
1½	8	3.6	16.5	15	12.1	20.2
2	21	9.4	25.9	4	3.2	23.4
2½	16	7.1	33.0	8	6.5	29.9
3	8	3.6	36.6	11	8.9	38.8
3½	5	2.2	38.8	7	5.6	44.4
4	6	2.7	41.5	8	6.5	50.9
4½	5	2.2	43.8	10	8.0	58.9
5	7	3.1	46.9	2	1.6	60.5
5½	2	0.9	47.8	4	3.2	63.7
6	9	4.0	51.8	4	3.2	66.9
6½	5	2.2	54.0	5	4.0	70.9
7	5	2.2	56.3	3	2.4	73.4
7½	12	5.4	61.6	2	1.6	75.0
8	13	5.8	67.4	3	2.4	77.4
8½	5	2.2	69.6	2	1.6	79.0
9	7	3.1	72.7	3	2.4	81.4
9½	1	0.4	73.2	1	0.8	82.2
10	6	2.7	75.9	1	0.8	83.0
Greater than 10	54	24.1	100.	21	17.	100.

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Table 2.
EVALUATION OF M-113 EXITING PERFORMANCE

M-113 Capability	Percent of Banks	
	Eastern U. S.	Thailand
GO	25.9%	23.4%
MARGINAL	15.6	27.5
NO-GO	58.5	49.1

SLOPE AND SOIL STRENGTH

High soil strength is of obvious benefit to the exiting vehicle when the bank approximates a uniform slope. When the bank approximates a step, the situation is reversed. Vehicles exit on step-type banks by bulldozing and excavating (with tracks or wheels) until a ramp is formed. In this case, there is an optimum condition where the soil strength is low enough to allow a ramp to be formed and high enough to support the normal and shear loading of the vehicle.

Tracked vehicles with blunt, flat, front ends and wheeled vehicles with long front overhangs or low bumpers have the most difficulty exiting on step-type banks. For example, consider a vehicle with a front bumper 8-in. high and 6-ft wide, with a net tractive force of 10,000 lb. The bulldozing resistance on the bumper -- only 15.9 psi (a relatively low value) -- will stop the vehicle. The M-113 has a tractive effort of 15,000 lb under favorable conditions and a near-vertical frontal area of approximately 1,740 sq in. A bulldozing resistance of less than 9 psi on this frontal area is sufficient to prevent this vehicle from exiting.

Vegetation, even light vegetation such as grass, can produce a soil condition which will prevent exiting. Vegetation also tends to maintain the bank in a step configuration. For example, when exiting tests were conducted on the French Canal in the Canal Zone of Panama, it was observed that a step-like bank configuration had remained relatively unchanged over

a period of sixty years, apparently because of the heavy tropical vegetation.

On banks which approximate a uniform slope (as opposed to those which approximate a step) the ability of the vehicle to exit is governed by the net traction that can be developed. Any given soil has a finite soil strength. When the soil is formed into a sloping surface, part of this strength is mobilized just to maintain the slope. This means that the soil strength available to support and supply tractive effort to the exiting vehicle is less than that for the same soil when level.

An unpublished analysis by P. W. Haley shows the following relationship between tractive effort and gross vehicle weight as a function of slope angle and soil internal friction angle for dry sand:

$$\frac{\text{Gross Tractive Effort}}{\text{Gross Vehicle Weight}} = \tan \varphi \cdot \cos \beta - \sin \beta \qquad (17)$$

where
$$\varphi = \text{soil internal friction angle}$$
$$\beta = \text{bank slope angle}$$

Equation (17) is plotted in Figure 19 for various values of φ and β. It is emphasized that this relationship was developed for dry sand. Wet sand, or a cohesive soil, can have appreciably more strength than would be predicted from Eq. (17).

RIVER MAGNITUDE

The size of the river to be crossed has an effect on exiting, because river current and depth generally increase with width. Recent tests at the U. S. Army Tank-Automotive Command indicate that all existing standard U. S. Army floating vehicles are uncontrollable in currents which equal one-half the maximum still-water speed of the vehicle.[*] The effect of

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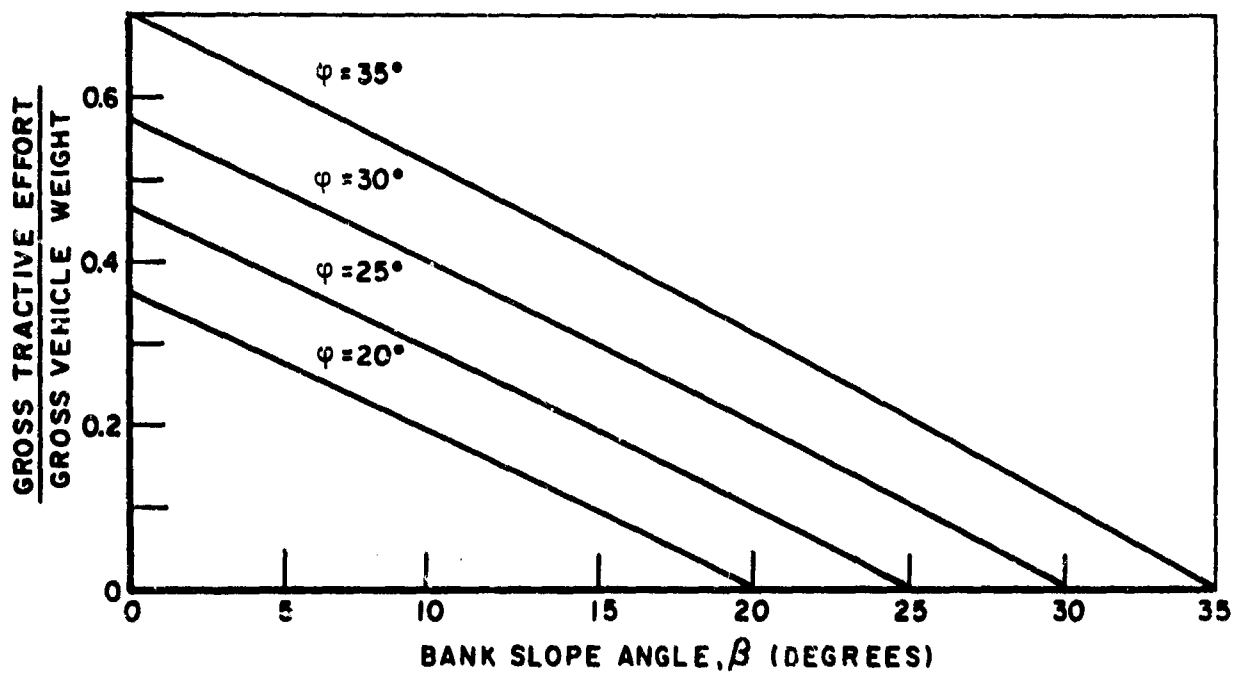[*] The only significant exception: the LARC V.

FIGURE 19. PLOT OF EQUATION 17, WHICH RELATES
VEHICLE TRACTIVE EFFORT TO BANK SLOPE ANGLE
(β) AND SOIL INTERNAL FRICTION (φ)

current, is, therefore, to force the vehicle to exit at a random point on the opposite bank, as opposed to a location selected for ease of exit. River depth is a factor, in that a vehicle exiting from a floating position has significantly less traction available, during the initial phase of egress, than when exiting from a fording situation. As previously noted, for example, the slope-climbing ability of the M-113 is reduced from 60-percent to 30-percent dry-slope capability when negotiating a water exit.

An additional factor involving a floating vehicle was observed during tests with the M-113. During swimming, a bow wave is formed in front of the vehicle. If the bank is sufficiently steep, this wave is reflected back from the shore, thus forcing the vehicle away from the shore before it can develop sufficient traction to remain in contact with the bank. Therefore the vehicle is not able to use its momentum as an aid when exiting.

Tables 3 and 4 show river width-and-depth data from field surveys.[26,27] These data show that most of the rivers are less than 100-ft wide and less than 3-ft deep. However, it should be noted that even small, shallow rivers frequently pose severe exiting problems.

ENTRANCE AND EGRESS WINDOWS

Two accepted generalizations are (1) that rivers normally meander back and forth across their own alluvium and (2) that the bank and stream bottom-surface profiles change predictably throughout a stream meander. We have seen that the banks on the outside of a meander are typically steep, and those on the inside of a bend (the shoal) are typically gentle. Bank slopes on intervening straight reaches are usually more like cut banks than shoals, and generally make poor selections for egress points.

An examination of the stereo pairs in Figs. 20 through 22 graphically illustrates these points. All photographs (scale 1:7000) were taken in the vicinity of El Real in Southeastern Panama. The rivers are confined to their own flood plains. (Climatically , T_{bio} = 26.7°C and P = 1800 mm with an 8-month wet season.) Figure 20 shows the steepness of cut banks

Table 3.
FREQUENCY OF RIVER SURFACE WIDTH[26,27]

River Surface Width (ft)	Eastern U. S.		Thailand	
	Rivers Surveyed	Percent	Rivers Surveyed	Percent
20 - 50	43	38	27	43
50 - 100	26	23	13	21
100 - 150	10	9	5	8
150 - 200	6	5	7	11
200 - 250	5	4	2	3
250 - 300	6	5	3	5
300 - 350	3	3	1	2
350 - 400	1	1	1	2
400 - 450	4	4	0	0
450 - 500	3	3	0	0
500 +	6	5	4	6
	Total 113		Total 60	

Arithmetic mean width	267 ft	171 ft
Geometric mean width	94 ft	82 ft
Median width	71 ft	60 ft

Table 4.

FREQUENCY OF RIVER DEPTH[26,27]

River Surface (ft)	Eastern U. S.		Thailand	
	Rivers Surveyed	Percent	Rivers Surveyed	Percent
0 - 1	22	19.5	3	5
1 - 2	29	25.5	10	17
2 - 3	21	19	15	25
3 - 4	14	12.5	1	2
4 - 5	6	5	7	12
5 - 6	2	2	2	3
6 - 7	4	3.5	4	7
7 - 8	0	0	2	3
8 - 9	2	2	4	7
9 - 10	2	2	4	7
10 - 11	0	0	2	3
11 - 12	1	1	1	2
12 - 13	1	1	C	0
13 - 14	1	1	0	0
14 - 15	1	1	2	3
15+	6	5	3	5
	Total 112		Total 60	

	Eastern U.S.	Thailand
Arithmetic mean depth	4.02 ft	6.14 ft
Geometric mean depth	2.55 ft	4.53 ft

FIGURE 20. STEREO PAIR OF A RIVER IN AN
ALLUVIAL PLAIN IN SOUTHEASTERN PANAMA
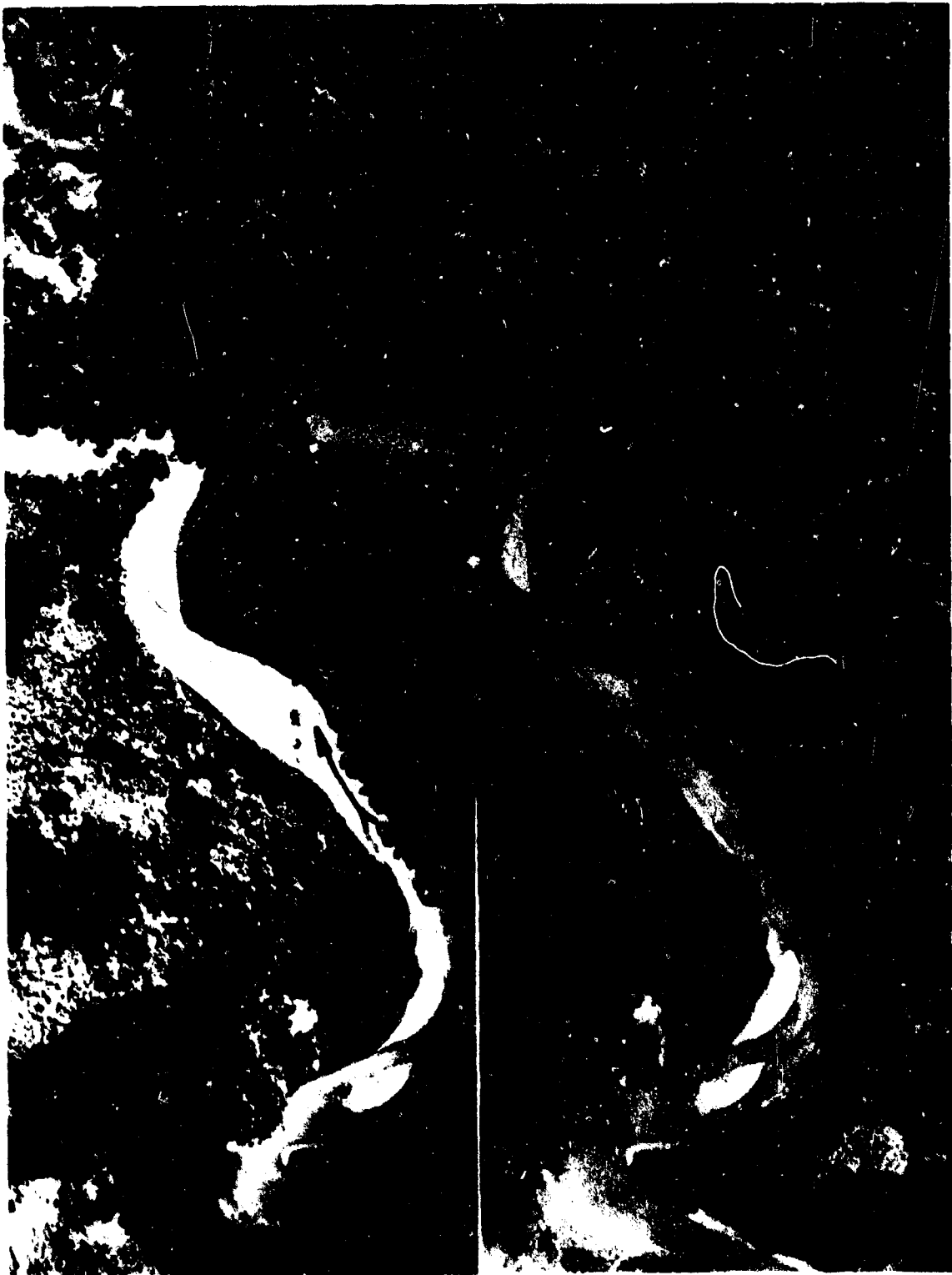
FIGURE 21. STEREO PAIR OF A SMALL
RIVER IN SOUTHEASTERN PANAMA

FIGURE 22. STEREO PAIR OF A LARGE RIVER
MEANDER IN SOUTHEASTERN PANAMA

and the complexity of vegetation on them, the gently sloping shoal areas (typically devoid of forest vegetation), and the steep slopes and forest vegetation lining the banks of the straight reaches. Figure 21 shows that the same principles apply in an area of undisturbed primary forest. Forest cannot advance onto these areas. Figure 22 illustrates all the points of Fig. 21 but for a larger river.

It has been well established that the steeper cut banks are not good egress points on the upper flood plain of relatively small streams.[13] Along the same stretches of these rivers, shoals are traversed with ease.

In alluvial fan or delta areas, however, it may be desirable to select the cut bank or one along a straight reach as an egress point. Here, the alluvium is composed of fine particles. The water level normally is very close to the top of the channel and frequently overflows its banks. With a soil moisture content that is constantly near saturation, delta areas are characterized by soft banks (particularly shoals), swamps, and natural levees. The levees consist of coarser, stronger soil particles and actually form the stream banks. Under these conditions, the shoals would probably be untenably soft and the cut banks, by comparison, relatively strong. Because the water level is usually close to the top of the bank, bank heights are not as critical a problem as farther upstream. Furthermore, extensive forest vegetation is not normally associated with these areas (primarily because of cultural influences), and may therefore be considered a less likely deterrent to egress.

As a consequence, entrance and egress points in the flat, expansive delta regions should be selected on the outside bank of a meander. Special care is required for negotiation, because this location usually has the maximum current velocity and possibly an undertow current as well. There is little choice in the matter of selection; the shoals are soft and their reaches often long.

The problem of defining the number of possible entrance and egress windows (N_w) is "simply" that of determining the number of meanders per unit of straight-line distance along the nominal river course. Leopold's recent work[10] indicates that the degree of stream meandering increases as the fall of the stream decreases, so the number of windows may be expected

to increase as the stream approaches the apex of its delta. For a stream
in an alluvial plain, the incremental fall decreases with distance from
the source.* The only way a stream can maintain dynamic equilibrium is for
it to develop meanders, and these, in turn, must become progressively
closer together.

To approximate a numerical relationship,** first let it be assumed
that the ratio of the wavelength of the stream , λ , for one complete
meander cycle to the radius of curvature , r_c , of the meander loop (see
Fig. 23) is proportional to the topographic slope; and secondly let it be
assumed that topographic slope varies from a maximum of 5 percent, at the
point where the river requires full-floating vehicles, to a minimum of
1 percent at the boundary of a tidal delta (tidal waterways thus excluded).
From Leopold,[10] freely interpreted,

$$\frac{\lambda}{r_c} > 5$$

indicates a mountain (destructional) stream. A vehicle cannot reasonably
be expected to traverse such an area, streams or no streams. Also,

$$\frac{\lambda}{r_c} > 3$$

indicates tidal deltas. If the ratio is less than 3, meanders will close,
forming connecting links and oxbow lakes.

Let L/λ be the ratio of stream channel length to straight-line
distance travelled by the stream. From Leopold,[10] L/λ varies from 1.3

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*Hack[12] proves that the fall (or stream-bottom slope) decreases from source
areas to the mouth of the stream in a hyperbolic form.

**It must be emphasized that the relationships here presented have not
been fully verified.
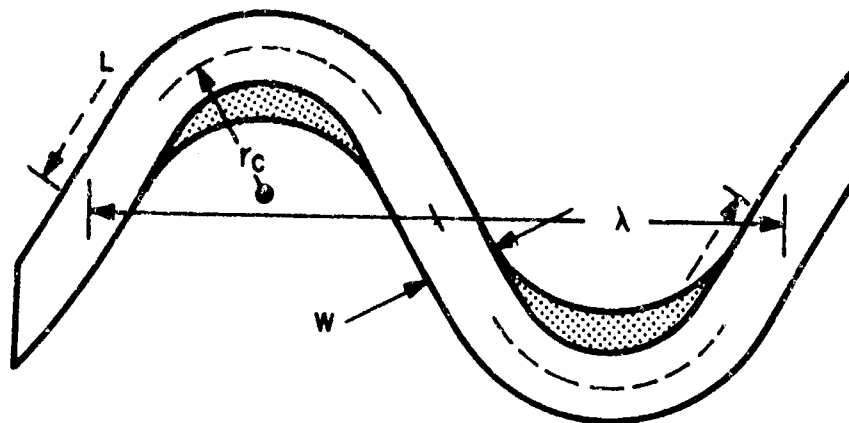
w = width of channel
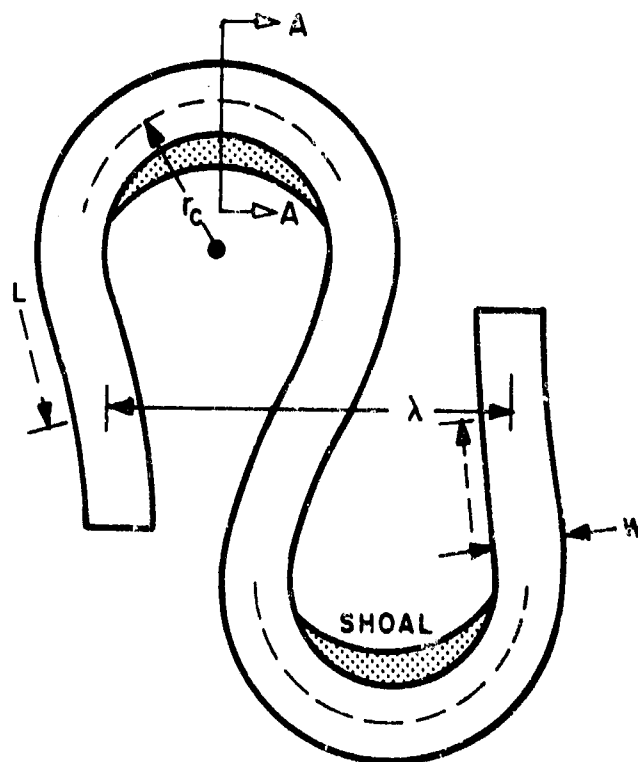λ = wavelength
L = length of channel
r_c = radius of curvature

FIGURE 23.   DEFINITION OF TERMS RELATING TO A RIVER MEANDER [10]

81

to 4.0 in nature. At values of

$$\frac{\lambda}{r_c} = 5 \ , \ \frac{L}{\lambda} = 1.4$$

and at

$$\frac{\lambda}{r_c} = 3 \ , \ \frac{L}{\lambda} = 3.6$$

if the curve approximates a sine wave. At two meander curves per wavelength, and one entrance or egress window at each curve,

$$N_w = 2(1.4) = 2.8 \ \text{at 5\% terrain slopes}$$

and

$$N_w = 2(3.6) = 7.2 \ \text{at 1\% terrain slopes}$$

Therefore,

$$N_w \simeq 7.2 \ S^{0.586}$$

where

N_w = number of entrance or egress windows (shoals) per mile of straight-line distance along the stream

S = the nominal terrain slope as might be determined from contours of a topographic map

It is suspected that there may be a scale factor which is not accounted for in this simplified equation. An attempt at refinement might be made by setting

$$N_w \cdot w = 7.2 \ S^{0.586} = CS^n$$

where C and n are empirical constants, and checking against data which can be derived from airphotos.

Chapter 8

RECOMMENDED WATER-EXIT SLOPE REQUIREMENTS

For a number of years, military requirements for new vehicles have included a section on river crossing. This part of the requirement usually stated that the vehicle "must be able to cross inland waterways." No actual performance levels were indicated.

In the past two years, there has been a significant change. River crossing has been divided into three areas of consideration.

     (a) Egress

     (b) Ingress
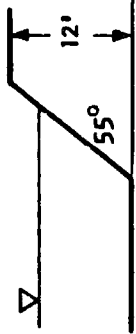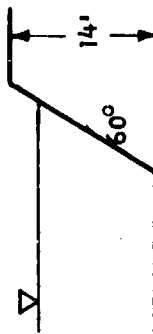
     (c) Floating and swimming

Of these, egress has recently received the most attention, because of the severe problem with respect to military-vehicle capability, even when the river is shallow enough to ford.

A recommended slope requirement has been developed by the Land Locomotion Division of the U. S. Army Tank-Automotive Command in conjunction with the Davidson Laboratory of Stevens Institute of Technology. It is summarized in Tables 5 and 6.[*] The tables show the type of river banks different vehicle classes should be capable of negotiating. A limited amount of soil data, the soil angle of internal friction, cohesion, and grain-size distribution are included. The tables were developed from field surveys of rivers[26,27] and represent the best available environmental information at this writing. It is anticipated that these recommended requirements will undergo continual revision and expansion as additional data become available.
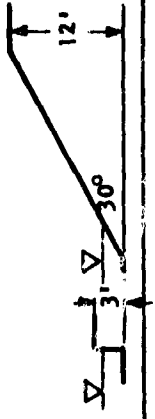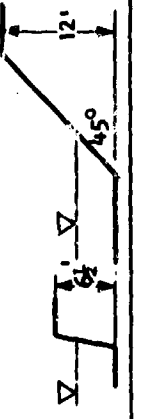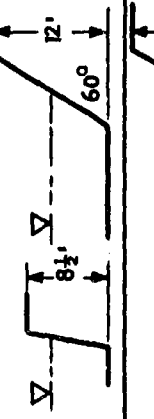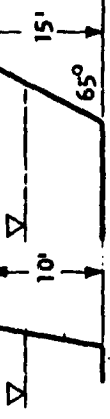
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[*] It must be emphasized that this is, at present, only a <u>recommended</u> requirement. No official approval is implied.

Table 5

RECOMMENDED RIVER EGRESS AND INGRESS REQUIREMENTS
(Tropical Areas)

Vehicle Class	Percent of Banks Vehicle Will Exit On	Bank*		Water Depth (ft)	Soil Cohesion (psi)	Soil Friction Angle (deg)	Slope Profile
		Height (ft)	Slope (deg)				
Wheeled Tactical	39%	9	35	4-3/4	0.75	10°	35° / 9'
Tracked Tactical	67%	12	45	6	1.0	15°	45° / 12'
Current Combat	77%	12	55	9	1.5	20°	55° / 12'
Future Combat	83%	14	60	11½	2.0	25°	60° / 14'

*Specified with no cover, grain-size distribution 95% of fine gravel or finer (U.S.B.S. Classification).

Table 6

RECOMMENDED RIVER EGRESS AND INGRESS REQUIREMENTS
(Temperate Areas)

Vehicle Class	Percent of Banks Vehicle Will Exit On	Bank 1*		Bank 2**		Water Depth (ft)	Soil Cohesion (psi)	Soil Friction Angle (deg)	Slope Profile
		Height (ft)	Slope (deg)						Bank 1 / Bank 2
Wheeled Tactical	37%	3	90°	12	30°	2	0.5	26° to 15°	
Tracked Tactical	52%	6½	80°	12	45°	4	0.75	31° to 20°	
Current Combat	67%	8½	80°	12	60°	6	1.0	35° to 25°	
Future Combat	76%	12	80°	15	65°	8	1.5	35° to 25°	

*Specified with vegetative cover, minimum 12-in. root depth, grain-size distribution 95% of fine gravel or finer (U.S.B.S. Classification).

**Specified with no vegetative cover, grain-size distribution 95% of fine gravel or finer (U.S.B.S. Classification).

Table 5, for tropical areas, was developed from river survey data taken in Thailand. A uniform slope with a relatively high water level is indicated. Table 6, for temperate areas, was developed from a survey of rivers in the United States. Lower water levels are indicated, but two types of banks occur: one is a uniform slope,[*] the other is a vertical, or near vertical step. Two banks are shown because the survey indicated that the step-type bank occurred with about the same frequency as the slope-type bank. Therefore, if the recommended requirement is to represent the environment, both types must be included.

It is possible to build a vehicle which, without additional assistance, could negotiate the banks shown for the "wheeled tactical" and "tracked tactical" vehicle classes. The COBRA and MEXA vehicles, which have pitch control, are examples. The banks shown for "current combat" and "future combat" will probably require that the vehicle be equipped with an exiting aid. The amount of force the aid must produce, for the slope-type banks, can be estimated by using the method shown in Fig. 24.

Ingress performance may be determined by the ability of the vehicle to enter the water over the banks shown in Tables 5 and 6. The ingress problems are concerned primarily with swamping and the ability of the engine and transmission to operate on the steeper slopes.[**] Existing military engines and transmissions can operate at angles of about 30 deg. At higher angles, the oil pick-ups on both the engines and converter-type transmissions become ineffective. Many gasoline engines also have carburetion difficulties at the higher angles. Thus, to meet the requirements of Tables 5 and 6, basic power-train design changes will be required.

Present floating and swimming performance requirements include the ability to cross a river with a stated current velocity and a minimum water speed. These are considered inadequate, because they do not relate properly to the river-crossing problem. The Land Locomotion Division and

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[*] Of course, actual slopes are not uniform.

[**] These problems are, of course, also present for egress, but they are usually not controlling.

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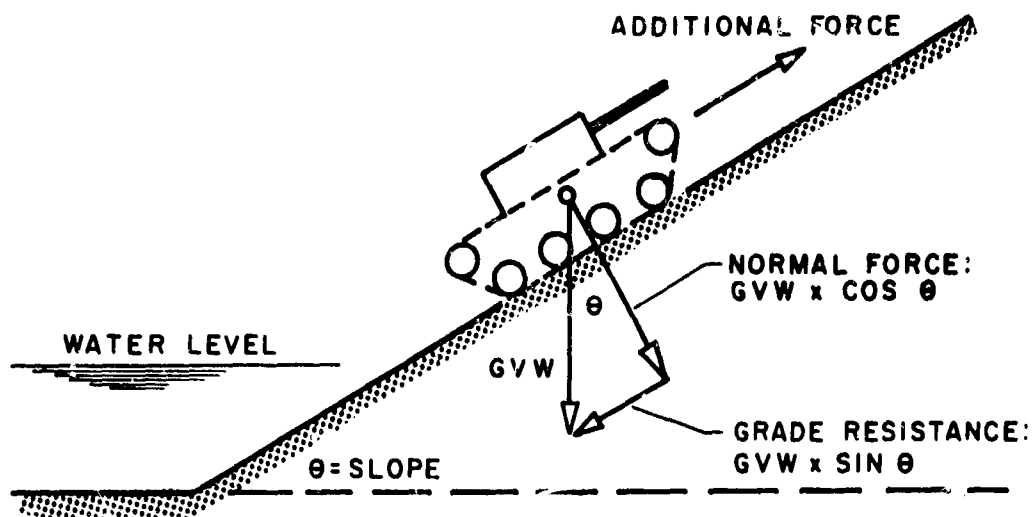
(1) Vehicle data required.
    (a) Gross vehicle weight (GW), lb: W
    (b) Ground contact area, sq. in.: A

(2) Bank data required.
    (a) Bank slope, deg: θ
    (b) Soil cohesion, lb/sq. in.: c
    (c) Soil friction angle, deg: φ

(3) Calculate traction achieved from cohesion , T_c .
    T_c = ground contact area x soil cohesion
    t_c = A x c

(4) Calculate traction achieved from soil internal friction , T_φ .
    T_φ = normal force x tangent of soil friction angle
    t_φ = W x cos θ x tan φ

(5) Calculate total traction , T_T .
    T_T = traction from cohesion + traction from soil
           internal friction
    T_T = T_c + T_φ

(6) Calculate grade resistance , R .
    R = GW x sin θ

(7) Calculate additional force necessary to negotiate slope , F .
    F = grade resistance - total traction
    F = R - T_T

(8) Calculate percentage of GW that additional force represents.

$$\% \text{ of GW} = \frac{\text{additional force}}{\text{GW}} \times 100 = \frac{F}{\text{GW}} \times 100$$

FIGURE 24. SIMPLIFIED METHOD FOR ESTIMATING AUXILIARY FORCE
REQUIRED TO EXIT ON A FIRM, UNIFORM SLOPE

the Davidson Laboratory are presently conducting tests and analyses with
the objective of improving and quantifying these requirements.

CONCLUSIONS

In the study of rivers, the state of the art as exemplified by the many theories of hydrology is highly developed, but its application to terramechanics is only in the most rudimentary form.

RECOMMENDATIONS

Mathematical models of the terramechanical aspects of river crossing appear to be the only economical solution to the complex problem of interrelating the vehicle and the riverine environment. The development of such models should be incorporated in future mobility research programs.

ACKNOWLEDGEMENTS

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DOCUMENT CONTROL DATA - R & D

Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author)	2a. REPORT SECURITY CLASSIFICATION
Davidson Laboratory, Stevens Inst. of Tech. Hoboken, N. J.	Unclassified
	2b. GROUP

3. REPORT TITLE

STUDIES OF OFF-ROAD VEHICLES IN THE RIVERINE ENVIRONMENT
Vol. III. Associated Environmental Factors

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)
Final

5. AUTHOR(S) (First name, middle initial, last name)

I. R. Ehrlich, R. G. Kolb, D. A. Sloss, and L. M. Corridon

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
April 1970	94	33

8a. CONTRACT OR GRANT NO. DA 30-069-AMC-789(T), DAAE-07-69-C-0356 and	9a. ORIGINATOR'S REPORT NUMBER(S)
b. PROJECT NO. Stevens Internal Research Funds	R-1285
c.	9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)
d.	

10. DISTRIBUTION STATEMENT

No. 1

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
	U. S. Army Tank-Automotive Center Warren, Michigan 48090

13. ABSTRACT

This report is a highly generalized overview of problems bearing upon the relationship of the riverine environment to vehicle stream crossings in unmapped or poorly mapped areas. Extractions from published works are used to emphasize (1) the need for reliable methods of predicting the nature of inland waters and neighboring terrain, from available climatic and geological data, and (2) the need for continuing and validating the theoretical study of vehicle performance in stream crossing and bank negotiation. It is made clear that a coordination of all factors into a comprehensive systems analysis would require a major effort, before the kind of evaluation method envisioned as the long-term goal of the current study can be achieved.

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
RIVERINE ENVIRONMENTS						
Prediction of Environment						
Prediction of Stream Characteristics						
OFF-ROAD VEHICLE MOBILITY						
Stream Crossing						
Bank Negotiation						
Environmental Factors						

DD FORM 1473 (BACK)
1 NOV 65

S/N 0101-807-6821

UNCLASSIFIED
Security Classification

A-31409